Tiv-Model: An empirically validated design methodology for complex space systems

By

Craig Montgomery Melville

A thesis submitted for the degree of Doctor of Philosophy

SMeSTech
Department of Design, Manufacturing and Engineering Management
University of Strathclyde
Glasgow, Scotland, UK

Submission: 14th March 2021

Supervisors: Prof. Xiu T Yan, Dr. Erfu Yang

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree. The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: ____________________

Date: _____________________

Acknowledgements

First, I would like to thank to my supervisors; Prof. Xiu Yan for his patience and guidance, without which I would not have completed this thesis, and Dr. Erfu Yang for his support and checking up on me from time to time.

Secondly, I would like to thank the DMEM staff for their advice and recommendations during the 8 long years this thesis took to manifest. Dr. Mark Post, Dr. Hillary Grierson and Dr. Avril Thomson assisted me with key personal advice. My colleagues at SMeSTech were also accommodating of my situation, and I would like to thank them.

Thanks to my friends for being in my corner. Special thanks to my best friends Kenny and Stacie, and my brother Daniel for cheering me on, I appreciate you guys. Much love to my mum and dad for supporting me financially and in every other way they could support their son. Finally, I want to thank my soulmate, Mariona, for putting up with my obsessive drive, and supporting me to the finish line. No words can describe the gratitude I feel towards you. I love you.

This thesis is dedicated to my grandmother, May, who missed seeing me grow up.

Abstract

In response to emergent space systems engineering industry challenges, this thesis explored work on the following;

1. The development of engineering design methodologies, following a design process and proposing a baseline of requirements for new methodologies called the “Methodology Requirements Document”.
2. A new design engineering methodology called the “Tiv-Model”, which combines novel academic research into a space systems engineering life cycle model that addresses the emergent challenges.
3. A procedure for verifying and validating design models, based on an existing technique called the “Validation Square”, incorporated to boost the waning confidence industry drivers have of academic models.

Through literature research, the Methodology Requirements Document is formed, and the Tiv-Model is created with the aim of optimising the development of space systems. Its novel aspects include a model-based verification technique (called multi-perspective modelling), a focus on teachability for novice engineers and incorporation of other new academic findings, to utilise useful research. The verification and validation of the Tiv-Model is used as an example to create a procedure for academics to validate their own models. A combination of comparative benchmark studies and a focus group was used to continuously improve the model and drive it through the design process.

The Tiv-Model rated better in student projects than its benchmark (V-Model) in 13 out of 24 survey categories in a t-test study, and underwent changes requested by industry veterans to finalise the model.

List of publications

Book chapters

Melville, C., & Yan, X. T. (2016). Tiv-Model - An attempt at breaching the industry adoption barrier for new complex system design methodologies. In P. Hehenberger, & D. Bradley, *Mechatronic Futures* (pp. 41-57). London: Springer.

Conference papers

Melville, C., & Yan, X. T. (2015). Universal connection interface for modular and swarm space robotics. *IET, IMechE, SSI and SMeSTech Space Robotics Symposium.* Glasgow.

Journal papers

Yan, X. T., Brinkmann, W., Palazzetti, R., Melville, C., Li, Y. L., Bartsch, S., & Kirchner, F. (2018). Integrated Mechanical, Thermal, Data, and Power Transfer Interfaces for Future Space Robotics. *Frontiers in Robotics and AI*.

Nomenclature

Abbreviation	Definition
AOCS	Attitude and Orbital Control System
AOO	Announcement of Opportunity
BOL	Beginning of Life (in reference to spacecraft mission)
CAD	Computer Aided Design
CAS	Computer Aided Simulation
CDF	Concurrent Design Facility
CDR	Critical Design Review
COTS	Components off-the-shelf
C-QuARK	A problem-solving technique: Consider, Question, Aware, Reasoning, Knowledge
CSE	Complex Systems Engineering
CSI	Complex Systems Industry
DfX	Design for X, when the design is optimised around 1 or more concepts
DoF	Degrees of Freedom
DRM	Design Research Methodology
DRR	Disposal Readiness Review
DTO	Design to Order
ECSS	European Cooperation for Space Standardisation
EOL	End of Life (in reference to spacecraft mission)
EPV	Empirical Performance Validity
ESA	European Space Agency
ESV	Empirical Structure Validity
FDA	Food and Drug Administration
FMEA	Failure Modes and Effects Analysis
FRR	Flight Readiness Review
GEO	Geostationary Equatorial Orbit

GPS	Global Positioning System
IASB	Royal Belgian Institute for Space Aeronomy
ICH	International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use
IDE	Integrated Design Environment
IDM	Integrated Design Model
IKTD	Institute for Engineering Design and Industrial Design
ISO	International Standards Organisation
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit (<10,000 km)
LEOP	Launch and Early Orbit Phase
LOD	Level of Detail
MA	Manufacturing and Assembly
MCR	Mission Concept Review
MDP	Mechatronic Design Process
MDR	Mission Design Review
MEO	Medium Earth Orbit (10,000-25,000 km)
NASA	North American Space Agency
NEO	Near-Earth Object
NOAA	National Oceanic and Atmospheric Administration
NPR	NASA Procedural Requirement
OOS	On-Orbit Servicing
PDP	Product Design Process
PDP	Product Design Process
PDR	Preliminary Design Review
PDS	Product Design Specification
PLM	Product Lifecycle Management
PRR	Production Readiness Review

QFD	Quality Function Deployment
RFP	Request for Proposal
SAR	System Acceptance Review
SDR	System Definition Review
SIR	System Integration Review
SOW	Statement of Work
SRR	System Requirements Review
TDM	Total Design Model (Pugh's model)
TPV	Theoretical Performance Validity
TRIZ	"Theory of the Resolution of Invention-related Tasks" (English translation)
TRR	Test Readiness Review
TSV	Theoretical Structure Validity
USP	Unique Selling Point
V-Square	Validation Square

List of figures

List of tables

Contents

Chapter 1

Introduction and overview

The aerospace and space systems engineering industry faces many challenges with regards to the design process. This thesis proposed to address those challenges through the improvement and development of engineering design methodology research. The primary conclusion from the preliminary research was that many of the challenges faced can be addressed by introducing novel academic concepts into the product lifecycle. The completion of this thesis work resulted in three key outputs. Firstly, a list of requirements for developing new engineering design methodologies, born of academic and industry research. Secondly, a life cycle model that was designed using these requirements, called the Tiv-Model. The third key output was the demonstration of verification and validation of new design models using a method called the Validation Square. The Tiv-Model acted as an example to show the step-by-step procedure to validate design models.

The first chapter is the introduction to the research and has a general overview of the work, as well as the research methodology, objectives, and contributions of the work.

In this chapter;

- **Thesis overview**
- **Research methodology**
- **Objectives**
- **Contribution statement**

1.1 Overview

The Complex Systems Industry (CSI) is a significant subsection of the systems engineering industry that spans aerospace, defence, maritime, robotics and so on. Complex Systems Engineering (CSE) products are distinct amongst other engineered products due to their scale, complexity and difficulty to model. CSE projects generally tend to be one-off, costly ventures that require many years of planning and design, often amalgams of diverse systems, created by organisations across many engineering fields. The Hubble Space Telescope is one such CSE project built to study the stars. The project was a joint effort by Marshal Space Flight Centre, Lockheed, Perkin-Elmer and other sub-contractors with the planning, design, building and management of the project. Initial cost for the project was initially costed at $300mil, however by the end of the project the total cost had rocketed to $2bil. (Dunar & Waring, 2012) This example of a CSE project blunder displays the risks of the industry in relation to traditional engineering. CSE projects are uncertain and costly due to complexity and scale. They have data, personnel and project handling needs, and so many traditional design techniques, such as prototyping, cannot produce results efficiently. (Andrews, 1998) For these reasons, this thesis researches further into the problems faced by CSE and the industry by conducting literature reviews. Lessons learned from other disciplines can be mirrored in space system engineering through common elements (Mandel & Chryssostomidis, 1972).

Research into these topics provides information on several more challenges, from systems engineering industry to project specific. One of the most poignant problems was the industry’s reluctance to adopt academia-born models and methods (Badke-Schaub, Daalhuizen, & Roozenburg, 2011). There were various reasons cited for their lack of faith but, most importantly, a lack of empirical data given to them to support usefulness of the models. To counteract this, a set of standardised guidelines for validating and verifying academic models was developed in this thesis. Furthermore, several opportunities were found within the literature regarding new practices, learning and problem-solving techniques, optimisation of the critical design path and musings with regards to how designers and organisations work. A brand new design lifecycle model was developed, called Tiv-Model, to demonstrate the knowledge gained from the literature, aimed at addressing the problems uncovered.

D.J. Andrews' (Andrews, 1998) and X. T. Yan/R. Zante's (Yan & Zante, 2010) models were major influences to the Tiv-Model. Both pieces were central in in its development as they provided coded solutions to some of the key industry challenges. Through analyses of existing models, suggestions from literature, and talking with industry professionals, guidelines for the development of a design methodology were derived. These guidelines were contextualised by design opportunities like solving CSI problems, accommodating novice engineers, maintaining organisational flexibility and design validation, and made up a design requirements document titled the "Methodology Requirements Document". This requirements document was the basis for the design of Tiv-Model. To validate the Tiv-Model, a scientifically grounded and heuristically driven method for verifying and validating design methodologies is proposed. Based off existing techniques, the core of this method is the Validation Square (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000). This verification method works on the premise that verification is checked at each level of the model, and that if every level of construction has been verified, the move to validation is a small leap of faith.

To verify the Tiv-Model, a series of studies were carried out with design engineering students. The first study was a short evaluative study to trial the Tiv-Model on an example problem, which revealed that it possessed all the core components of a life cycle model. The next study was a comparative study, with 3 iterations carried out to satisfy the requirements of the Validation Square method. This comparative study had groups of students use two models, the Tiv-Model and the V-Model, and report their perceived usefulness via survey. The students used the models to design an autonomous rover. The final study was a focus group, attended by space systems engineering industry members, who would offer their opinion and critique of the Tiv-Model. This study provided tips for improving the model and formed the final validation step.

After each study, the Tiv-Model was adjusted and improved based on the feedback. By the final iteration of the comparative study, the Tiv-Model outperformed the V-Model in 13 of the 24 measured categories in the survey, such as ease of use, perceived effectiveness and ease of implementation. This would prove the viability of the Tiv-Model, as it performed as good as or better than an accepted industry standard model.

1.2 Research summary

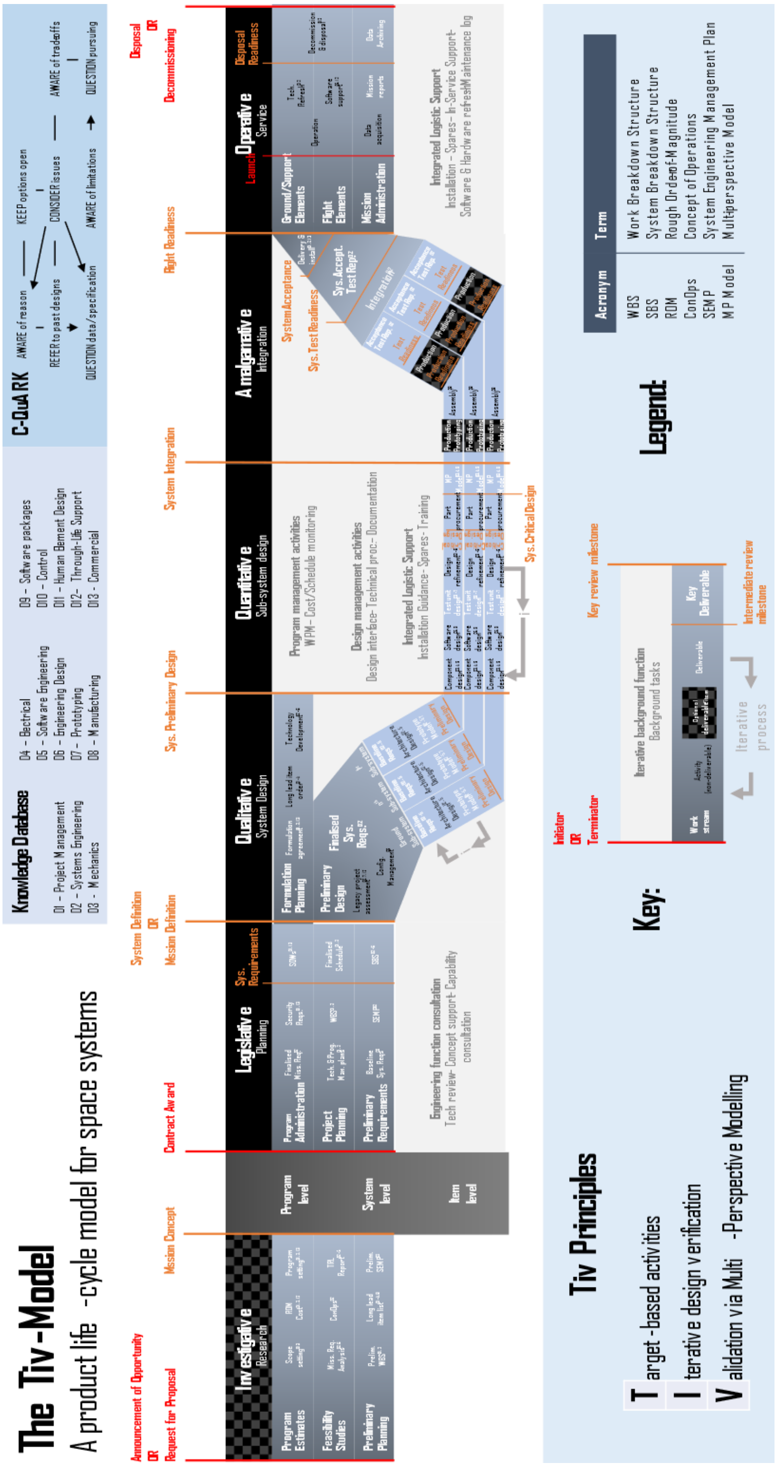


Figure 1-1 - The Tiv-Model, the full picture

The Tiv-Model (Figure 1-1) is a space systems life cycle model for use in the planning, design, creation and operation of complex space systems. The focus of the methodology is on quality improvement and the usefulness of the model comes from several aspects, its modular architecture will allow engineering organisations that adopt the Tiv-Model while making only moderate changes to the structure of the model. The model's integrity is maintained while accommodating the culture and methods of the organisation. The Tiv-Model operates on "deliverables", which are projected outcomes of design tasks, such as a Systems Engineering Management Plan (SEMP). Methods are not mandatory but recommended, such as using TRIZ for high detailed concepts, or brainstorming for high output, low fidelity concepts. The engineering lead can declare their own methods or procedures to be used foreach task so long as the deliverable is the outcome.

The Tiv-Model incorporates multi-perspective modelling, an approach that takes the data from many virtual and practical models such as thermal, stress and kinetic models and combines them into one amalgamated model. This means creating one model with all the key data present and fully interacting. Alternatively, a satisfactory compromise is to quantify how each of these models will react with one another. The reasoning behind adopting multi-perspective modelling is to improve the accuracy of digital simulation results whilst also focusing on digital prototyping to reduce prototype fabrication costs.

The complex system industry has both novice and veteran engineers. Veteran engineers often "carry" projects, especially with regards to knowledge and consultancy time. Novice engineers spend a lot of time figuring things out and consulting the senior engineers. To mitigate this, the Tiv-Model was developed focusing on novice engineers needs, reflected throughout the model in the mid-tier work package management procedure, and reflected in the lowest level with the inclusion of a problem-solving strategy built for novice engineers. This strategy, called C-QuARK (Ahmed-Kristensen, Wallace, & Langdon, 2001), is activated when encountering troublesome design challenge. The strategy sets out questions that the engineer should be asking themselves to encourage the flow of information, to uncover key insight into the solution.

Tiv-Model is optimised to cope with problem areas within the complex systems industry, such as the management of knowledge, parts and resources. This is all accommodated in an accompanying computer application, set up at the start of a project by the project lead. The timescale of the project and each stage is determined by the system design authority and project manager, as well as the tasks and methods used to achieve the deliverables. The application is user based, and personnel can be assigned to tasks, deliverables can be submitted as documents via the software. The software is a structural tool to manage the vast amounts of personnel and data required for complex design projects.

The creation of Tiv-Model served a dual purpose, firstly to create a methodology that is useful in the complex systems industry, and second to act as a guide for the creation and validation of engineering design methodologies. Packaged within the thesis is a steppingstone guide to the creation of design methodologies, using Tiv-Model as an example. A verification and validation method is also included, based on literature research from several disciplines. A standardised verification and validation structure for engineering design methodologies is needed to combat the lack of confidence industry has for academic model performance. Providing and promoting some standard way of proving the viability of a methodology will help ease the concerns of industry and create a grounded, healthy academic environment.

1.2.1 Research methodology

The research methodology adopted for this thesis is based on Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009), the basic diagram shown in Figure 1-2. DRM has four stages, with paths that allow for iteration of these stages, each accomplished by a basic means and delivering a set of outcomes.

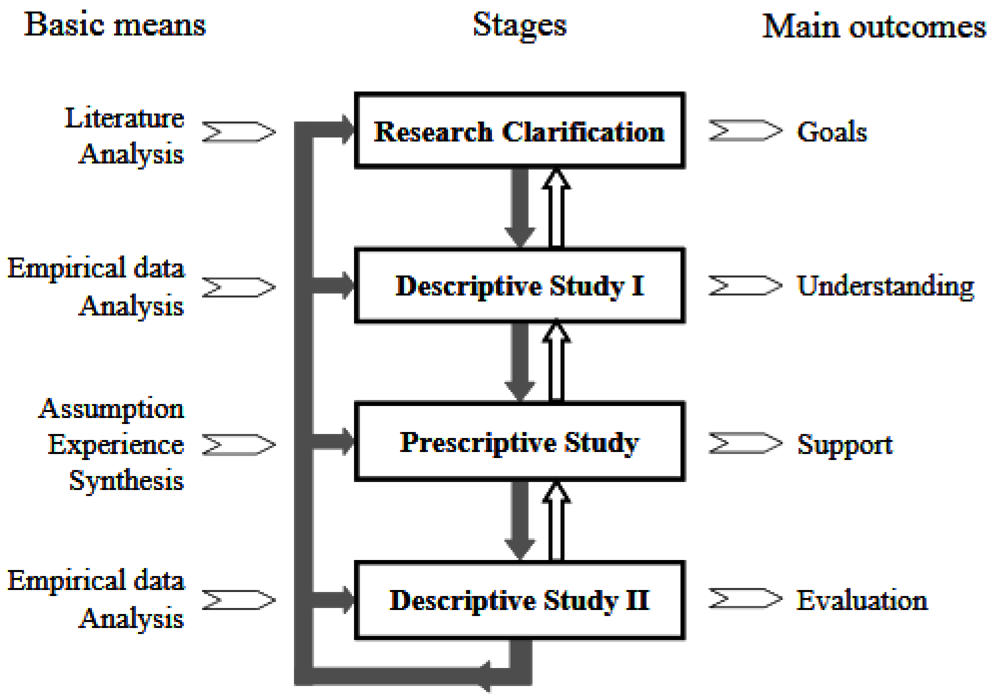


Figure 1-2 - DRM basic model (Blessing & Chakrabarti, 2009)

The design research undertaken was mapped to DRM following the suggested stage plan, Figure 1-3 is the summative model for the thesis' research. The four stages of DRM match the content presented in Chapter 1 through to Chapter 7 of the thesis. The first stage covered the initial background research, dedicated to contextualising the document and developing the research question. Stage 2 defined the problem with an additional literature review to define solution opportunities and gain knowledge for design methodology development. Stage 3 showed the developed methodology, called Tiv-Model, and validation method, called V-Square. A prescriptive study occurs here to "reality check" the development of the model. A second set of descriptive studies occur in stage 4, one of which is a larger scale study which retrieves empirical data from survey answers. The second study in that stage is a focus group with space system industry participants geared at validating the Tiv-Model. The Tiv-Model develops iteratively, as changes were made to the methodology based on feedback from each of the studies.

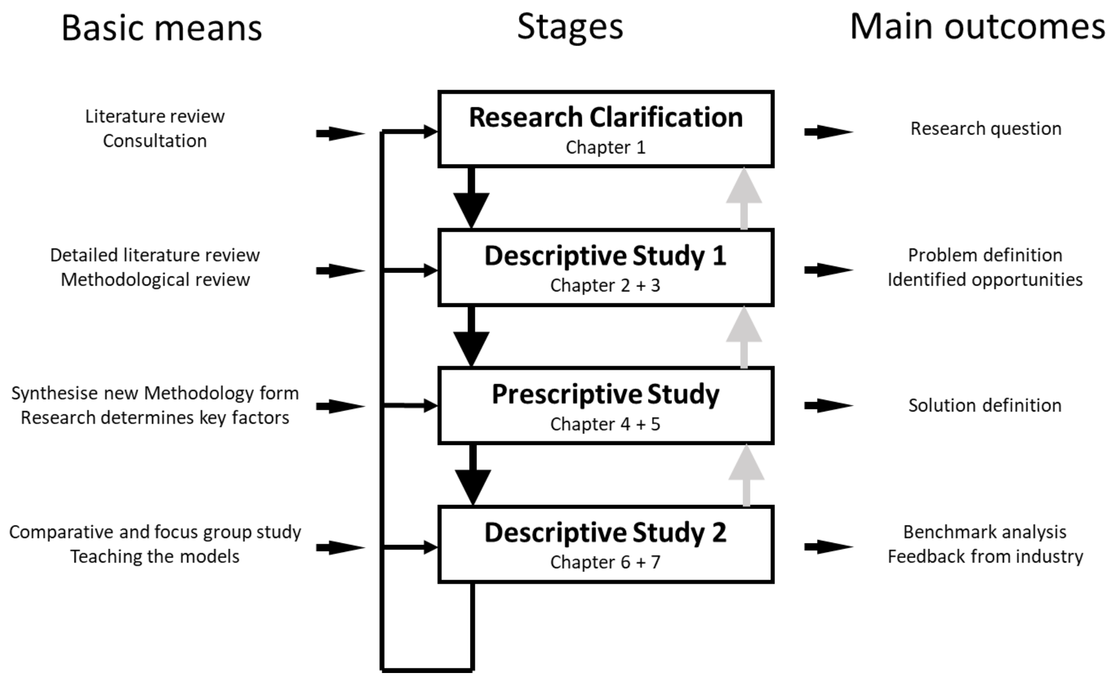


Figure 1-3 - Modified DRM model to show basic thesis plan

1.2.2 Motivations of research

Many methodologies have been created for the design of complex systems, some born of academic theory and others of industry expertise. Tiv-Model’s novelty is that it was designed with prominent issues in mind that plague the industry and engineers. The verification and validation problem shows industry’s grievances with the blue-sky academic world, as of the time of research no publication has been made that offers a comprehensive solution. This is further compounded with academia’s lack of systematic approach to testing and creation of design models. With these issues in mind, the research set out to achieve the following goals:

1. To generate a design methodology optimised for common industry challenges, such as prototyping, design validation and cost effectiveness.
2. To derive a systematic, reliable method for validating and verifying theoretical and practical integrity of engineering design methodologies.
3. To produce a guide for academic creation of new design methodologies based on the needs of specific projects or industry needs.

4. To create a support framework that aids learning the methodology, for academic and industrial application, and management of design resources such as staff, time and information.

1.2.3 Aim and Objectives of research

The common thread among all research areas in this thesis was the development of the Tiv-Model. It was developed to tackle the challenges facing industry and academia. Improving the engineering methodology design process was also a goal of this thesis. The Tiv-Model was an example, a use case and a solution to each of the challenges defined in this thesis. From this, the following research objectives were developed:

1. Define a set of design challenges that the complex/space systems industry is likely to encounter that should be addressed by academic research.
2. Develop a product lifecycle model for complex space systems that mitigates specific industry problems.
3. Compose a means of verifying and validating the theoretical and practical integrity of design methodologies with respect to relative performance.
4. Generate a process guideline aiding the development of future design methodologies using experience gained from the research.
5. Create a piece of computer software that helps support the management, education, and implementation of the developed methodology.
6. Use the design methodology as an guide for the creation of future models and the validation/verification method to demonstrate its success.

1.2.4 Projected contributions of research

The novel aspects and knowledge contributions from this research are:

1. Creation of an engineering design methodology for use with space and complex systems industry.
2. Generation of a series of design guidelines for development of design methodologies.

3. Generation of a method and experiment set for verification and validation of engineering design methodologies.
4. Documentation of a guide on the creation of engineering design methodologies.
5. Demonstrative model of Tiv-Model implemented into a digital tool.

1.2.5 Thesis content structure

This thesis follows an 8-chapter structure, outlining the progress of the thesis near-chronologically.

Chapter 1 – Introduction

The first chapter contains the basic overview, summary, and thesis statements.

Chapter 2 – Background research and developing the research question

The second chapter contains the necessary contextual background research to compound research opportunities posed in the literature and justify and frame the research question.

Chapter 3 – Problem definition, development of model and validation and verification

The third chapter then delved further into the academic research regarding design methodologies and how they should be developed and validated. Working on a combination of literature and personal experience, common ground was found as a foundation for best design practice. Verification and validation techniques were also uncovered and discussed in this section.

Chapter 4 – Design document for methodologies, PDS

The fourth chapter described and summarised the lessons learned from literature and other sources as a combined requirements document, called the “Methodology Requirements Document”. This contribution to knowledge was used as the basis of construction of the Tiv-Model and acts as a design document.

Chapter 5 – Solution definition and justification of Tiv-Model

The fifth chapter described the development outcome of the research conducted in Chapter 4, the Tiv-Model. The aspects, design decisions and justification of the Tiv-Model take place here. The Validation square and associated techniques are propose as candidates for standard Verification and Validation practice.

Chapter 6 – Applying verification method to the Tiv-Model in experimentation

The sixth chapter describes the experiment plan and how the Verification and Validation method is applied to the Tiv-Model as a standard procedure for methodology evaluation. This chapter displays the comparative study findings.

Chapter 7 – Validating the Tiv-Model via focus group

In the penultimate chapter, the Tiv-Model is put through one last round of study, with industry veterans scrutinising and criticising its theory and application. This final pass would act as a means of validation as the participants can be considered akin to the end user.

Chapter 8 – Results and discussion

The final chapter concludes the work and in the context of the study findings and proposes future work or changes based on these. The strengths of the weaknesses of the project overall will also be presented here.

Summary at a glance

- This work aimed on producing a solution to mitigate long standing and emergent challenges present in the world of system design engineering.
- The goals of the work were to provide several components that were geared toward an overall solution at the design philosophy level. The key binding goal was to re-think the engineering design process for systems.
- This was satisfied with three primary deliverables;

  1) A re-evaluated list of requirements for engineering methodology design
  2) An engineering design methodology created from those requirements
  3) A means of verifying and validating the research and methodology

- Thesis is 8 chapters long, covering all parts of the work process chronologically, with the final chapter being a summary.
- The research methodology used is a modified version of DRM, using iterative prescriptive and descriptive studies to refine the research.

Next…

- Background research into 6 key problem areas within the scope of the thesis
- Extraction and classification of potential research opportunities

Chapter 2

Background research

The goal of a thesis is to significantly contribute to knowledge, or the solution of a particular challenge in a given problem area. Thus, the first step here was to define the problem area. This thesis focused on both emergent and long-standing challenges in the complex systems engineering industry.

To generate the problem statement, relevant research into the problem areas was conducted. Here, the key findings of the background research were provided and categorised it into several areas. From this research, opportunities were derived for research contribution.

In this chapter:

- **Background research into problem areas**
- **Generating potential research opportunities**

2.1 Design

There were many definitions available for “design”, perhaps one of the most encompassing ones comes from James Armstrong (Armstrong, 2008):

> *“Design is recognised as an iterative creative process bringing about the development -physical and cultural- of ways meeting the identified needs.”*

He goes on to specify design engineering in a short list of tasks:

1. The definition of a need
2. The conception of response to that need
3. The organisation and management of the delivery of that response

These three core premises of design can be further broken down to stages of a timeline, commonly referred to as the engineering design process. There are many understandings of the design process that have been modelled, all containing similar, if not the same, basic stage formatting. In Table 2-1 below, several of these models are shown in comparison, aligning the stages that are equivalent to demonstrate the agreement literature has regarding the design process. The comparative view of these models, broken down to their stages, shows that the design process as a timeline is well understood and agreed upon by the literature, minor changes exist to capture nuances of specific problem areas. The column on the right of this table shows an interpretation of the common elements of these stages.

French's Model	Archer's Model	Cross' Model	Hill's Model	Roth, Binz and Watty's Model	Combined view of design
Need	Training	Exploration	State of the Art	Planning	Background
	Programming		Identification of need		Problem exploration
	Data collection				Need exploration
Analysis of Problem	Analysis		Conceptualisation		Analysis
Statement of Problem	Synthesis				Problem statement
Conceptual Design		Generation		Conceptual Design	Concept generation
Selected Schemes		Evaluation	Feasibility analysis		Concept feasibility
Detailing	Development		Production	Embodiment Design	Embodiment design
				Final Design	Design finalisation
Working Drawings	Communication	Communication			Design communication

Table 2-1 - Generic design process model comparison

Juster (Juster, 1985) helpfully summarises several author's work on the commonality of the design process and concedes that design is an iterative, stage by stage process of:

1. Recognition of need
2. Specification of requirements
3. Concept Formulation
4. Concept Selection
5. Embodiment of detail design

6. Production, sales, and maintenance

One of the more complex findings with the design process is that there is a slight contention surrounding its definition, shown in Powell and Jacques (Jacques, 1981) work. In short, three differing opinions came from expert sources regarding the design process:

- The design process should be inherently heuristic;
- The design process should be inherently systematic;
- The design process regardless of what it is, should not be imposed upon the designer.

This raises an interesting question: is there research that measures the performance of disorganised design process? In current understanding, it is safe to assume a more systematic approach is the default, and most research within that realm describes the design process as-is rather than should-be (Finger & Dixon, 1989). Since the time of these conclusions, research has provided insight into the optimisation of the design process, some of which was discussed in 0, but the question of a non-system/non-process approach to design could be a future opportunity.

2.1.1 Solution-oriented and problem-oriented strategy

On a similar note, the product design process and associated problems can be approached by designers in two different ways. The first is a solution-oriented strategy, involving the proposal of an initial solution that is adjusted as constraints, requirements and optimisation routes are explored. The second is a problem-oriented strategy, completely understanding the problem and requirements before any conceptual design takes place (Lawson, 2006) (Birmingham, 1997). Training and background were the two major influences in the final choice of approach in practice; typically, informal designers favoured solution-oriented strategies whilst academics preferred problem-oriented strategies (Lawson, 2006).

It is understood that the application and allowance of either of these strategies is an important component of the design process that allows designers to deal with various problems (Frost, 1992). Engineering design by its very nature is an ill-defined and complex problem (Jonassen, 2011) which, should be noted, is markedly different from the term "complexity"; this will be touched on later. This does not mean complex designs are ill-defined in brief. It is said to be ill-defined and complex because the problems presented by engineering have no one true path to the solution, nor only one solution total. Engineering befits the nature of a problem-oriented strategy as it is often a challenge that requires an optimised solution, as opposed to solution-oriented strategies which aim for low effort, adequately satisfying ones. (Hong & Choi, 2011)

2.1.2 Knowledge within product design

Knowledge exists in many forms and taxonomies both inside and outside of design context. Roth, Binz and Watty (Roth, Binz, & Watty, 2010) broke down academic knowledge models in the context of product and engineering design, including a derivative map of knowledge across the product design process (PDP). This map, shown in Figure 2-1**Error! Reference source not found.**, is the outcome of their literature review and empirical studies regarding design process and knowledge requirements.

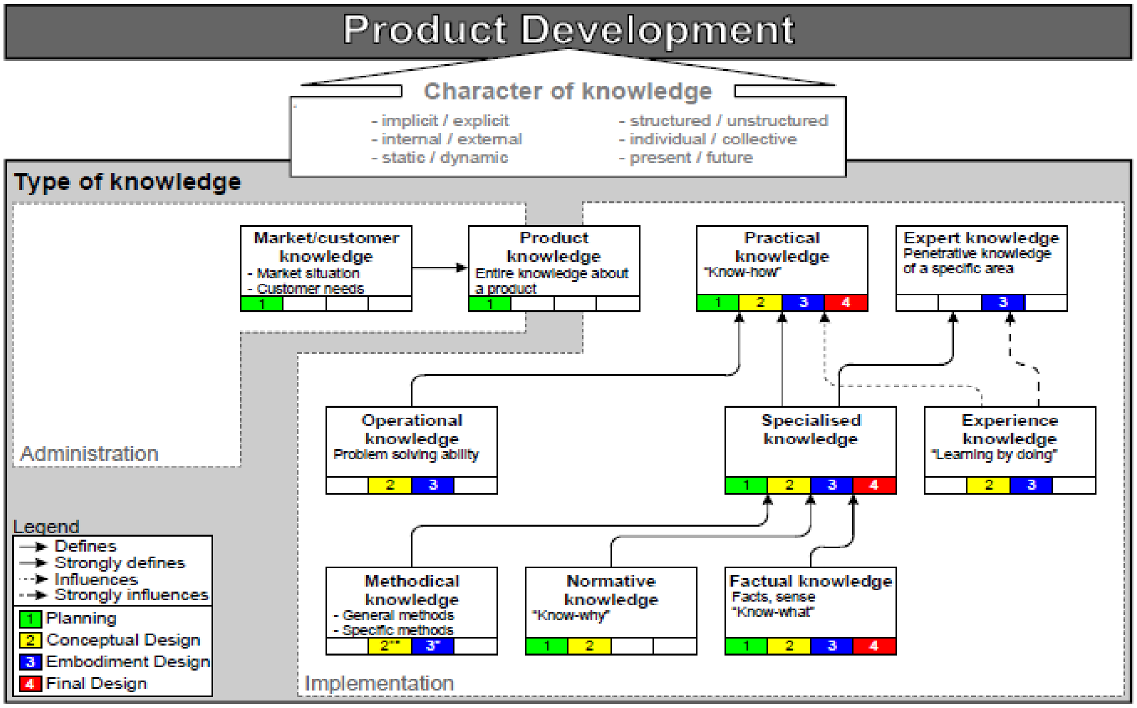


Figure 2-1 - General structuring model for PDP knowledge

The map specifies four fundamental design process stages, Planning, Conceptual Design, Embodiment Design and Final Design. These are classified as several knowledge types represented by rectangles in the graphic; there were 13 in the original and eventually narrowed down to 10 in the final iteration of the map. The map shows which knowledge type is required during each design stage and how each knowledge type influences the other. Understanding the knowledge needs of the designer during the design process helps with planning and resource allocation.

2.1.3 Knowledge of the novice designer vs experienced designer

Literature was available on the differences between novice and experienced designers, namely their performance and interpretation of design tasks. Ahmed-Kristensen et al. (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000) perform a comprehensive literature review within their paper, mapping the expert engineer’s thought process. Finger and Dixon (Finger & Dixon, 1989) have an all-encompassing literature review of mechanical engineering design, including a section on the behaviours and knowledge needs of novice and expert designers. Christiaans (Christiaans, 1992) found that experienced designers tend to gather more information about the task, whilst novice engineers took on the issues one at a time, and tend towards trial-and-error strategies. (Ahmed-Kristensen, Wallace, & Langdon, 2001) Novice engineers rely on deductive and backwards reasoning when approaching a design problem, experienced engineers combine this with visualisation and their own experience (Göker, 1997). This is supplemented by Manjula et al (Manjula, Waldron, Jelinek, Ownes, & Waldron, 1987) who demonstrated that expert designers have better visualisation overall. This may be due to the superior 2D/3D comprehension and spatial memory skills that the experienced engineer has (Gero, Tversky, & Gobert, 1999).

Research outside of the engineering domain has also revealed some insights into the design process, for example, in software design. Adelson and Soloway (Adelson & Soloway, 2007) and, Adelson and Freedle (Adelson & Freedle, 1988) find that a tool’s helpfulness is dependent on the user’s experience and their design knowledge. They find that, in general, novice designers will try and opt for tools, methods or information that constrain or limit their options. One skill new designers have is that they can flexibly adapt to the guidelines of a given methodology without really knowing them in-depth (Birkhofer, Jansch, & Kloberdanz, 2005). Knowing this, new designers con impose helpful design constraints by adopting a methodology to guide them.

2.2 Methodology

To define a methodology first one must define a method. Cross (Cross, 2000) gives a rough definition of a design method being…:

> *"...any procedures, techniques, aids or 'tools' for designing. They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process."*

Oxford dictionary solidifies the meaning of method as:

> *“A particular procedure for accomplishing something, especially a systematic or established one”*

This definition also lets one define what a group of interlinking design methods becomes: a design process. The definition of a methodology is heavily related to methods (Cross, 2000), which is:

> *“A system of methods used in a particular area of study or activity”*

Design methodologies are a set of design methods in series that form a process. It is not difficult to see the similar core concepts that methods and methodologies share. A method is a series of tasks accomplish some objective or deliver a desired output. Similarly, a methodology is a series of methods with the same effect. When compared in the same context, methodologies can be considered as large scale methods defined by the broadness of the goal in question.

2.2.1 The methodology house

To explain the concept of a methodology and its constructs, the example of a house is used.

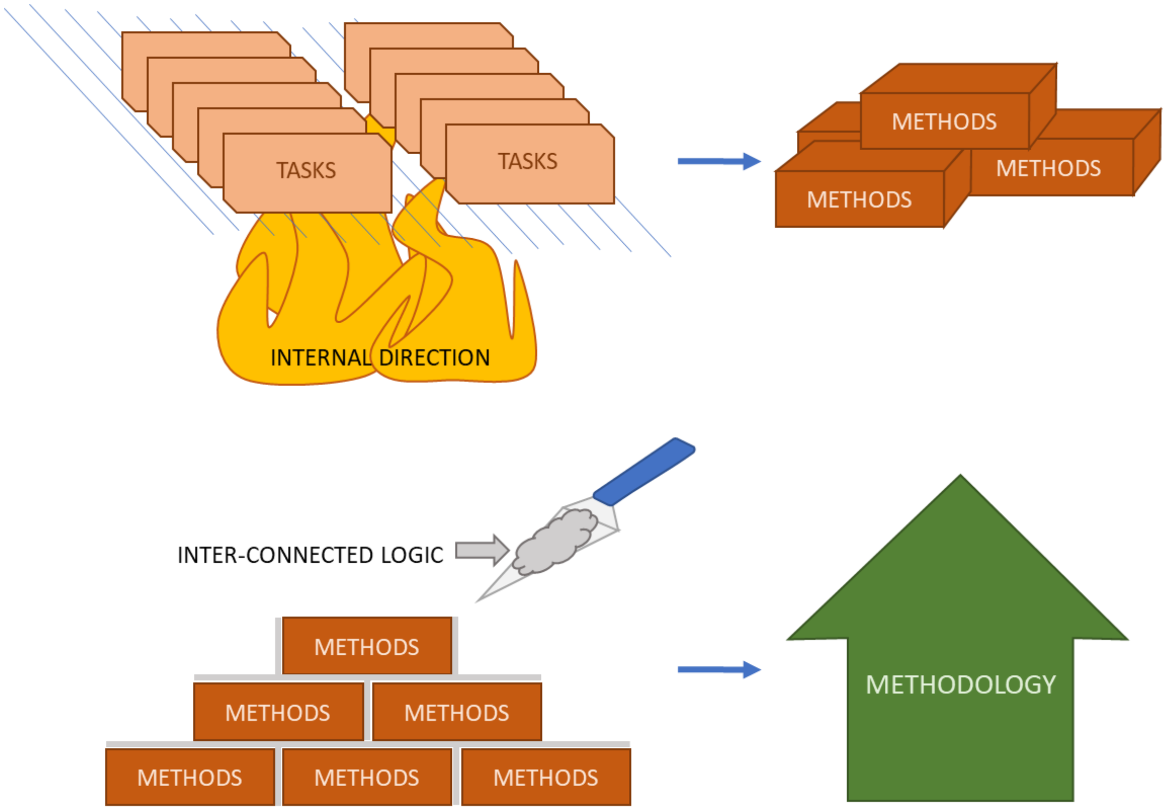


Figure 2-2 - The methodology house

A methodology is a house, its methods are the bricks. Houses are known to be made of bricks and that bricks are made of clay; pieces of raw clay are the individual tasks within a method. This clay is useless without fire hardening (given internal direction). In the same sense, the mortar used to build the house is the logical interconnections between each brick (i.e., the logic and purpose behind the methodology). Whether it is a brick or a house, each of those is made of smaller components that make up the whole, and each is contextualised by the intention. By looking at the methodology in this way, it can be shown that methodologies can be treated as large scale methods with purpose and logic behind it. Once this is established, tools and techniques used to evaluate methods can now be used to evaluate methodologies.

Evaluation of methods is well established in the literature researched; qualitative data is easy to come by for small scale method evaluation in engineering. Methodologies have an added layer of complexity and thus evaluation of methodologies takes considerably more effort. However, because they are of similar structure, it is feasible to use equivalent but grander means of evaluation. In the Methodology House example, if the means of evaluation is a set of scales then bricks can be weighed individually, but weighing all the bricks will not give the weight of the house. The mortar, the intra and interconnecting logic, must also be considered. Weighing mortar on its own would get very messy, so it must be put in a container because it is not solid like the brick. The viscous liquid state of the mortar represents an intangible and subjective context, and so to weigh it, it must be contained with reasoning (the bucket with which to weigh). This is the complication between the evaluation of methods and methodologies: not only does one need bigger scales but the mortar requires some logical containment. If the inter-method logic is accounted for, techniques used to evaluate methods can reasonably be used to evaluate methodologies. This subject is explored further later, in section 2.6.

2.2.2 Advantages of applying methodologies and models

It is agreed that the use of models and methodologies in the engineering design industry is very beneficial. As mentioned before in the design section, research on design outside of the paradigm of the design process is scarce or non-existent, possibly due to a natural inclination to systemise this task. For this reason, the benefits of following a model are summarised informally in this section. (O'Donovan, Eckert, Clarkson, & Browning, 2005)

Following an established engineering design model during the design process can improve project and company-wide transparency. Each member of the design team can check what others are doing and what they should be doing, breaking down the ambiguity in management and allowing engineers to see the bigger picture if they choose. Project planning and management becomes easier, and communication of tasks and ideas is fluid. No managerial “fog-of-war” clouds up the work environment or its channels and a common terminology base can be established.

The nature of a model aids planning on its own. Generally, models are based off previous design process experience or research, therefore costs, time scales, design tasks and milestone planning can be determined from the beginning of the project. The model is used here as a planning tool, allowing the project plan to be developed and refined early. Design process models could also assist with dynamic planning. Changes that need to be made at some point after the project started are unavoidable and experimenting with hypothetical scenarios will improve the overall design and resource/personnel allocation.

Clarkson and Hamilton (Clarkson & Hamilton, 2000) determined that finite pieces of information, such as files and documentation, should be specified by the design process model, which aids designers in their daily tasks. This also aids information exchange between tasks, stages and people as those finite pieces can be tracked and managed. Knowledge counts as a manageable asset.

The final, tangible benefit of employing a PDP model is using it as a frame of reference for training new employees and novice engineers. It gives context to the design process and organisational values. Visual models are preferable teaching materials over written procedure and assets.

2.2.3 Required components of design methodologies

Keller and Binz' (Keller & Binz, 2009) work on the requirements of design methodologies provides critical information for method evaluation. Their work uses literature to determine the most fundamental requirements for a multi-disciplinary design methodology and simplifies them into a list, relationships between the requirements are shown in Table 2-2.

A	**Revisability**	Validation
		Verification
B	**Practical relevance and competitiveness**	Innovativeness
		Competitiveness
C	**Scientific Soundness**	Objectivity
		Reliability
		Validity
D	**Comprehensibility**	Comprehensibility
		Repeatability
		Learnability
		Applicability
E	**Usefulness**	Efficiency
		Effectiveness
F	**Problem Specificity**	Problem Specificity
G	**Structure and Compatibility**	Handling Complexity
		Problem Solving Cycle
		Structuring
		Compatibility
H	**Flexibility**	Flexibility

Table 2-2 - Requirements on design methodologies (Keller & Binz, 2009)

The authors detail the meanings behind these phrases, but a simple explanation was provided here in this thesis.

A - Revisability

Determination that the methodology is satisfying the requirements of itself internally and externally.

Validation – The methodology is supposed to do the right things.

Verification – The methodology is supposed to do things right.

B - Practical relevance and competitiveness

Ensuring that the methodology is relevant on a commercial or academic level to justify its use.

Innovativeness – The ability for the methodology to be within its niche, providing a solution where there rarely is one.

Competitiveness – The methodology should be at least as good within its niche compared to its competitors, which are used in turn as a benchmark for evaluation.

C - Scientific soundness

Solidifying the theoretical rigidity of the methodology and its predictable or systematic standards.

Objectivity – The methodology is neutral and independent of human dispositions and does not bias the designer.

Reliability – The methodology should return similar results when the same data is input under the same scenario.

Validity – The methodology output is in line with the goals that it was designed for.

D - Comprehensibility

Making sure that the methodology is understandable on human terms, that it is clear in its instructions and that it can be learned.

Comprehensibility – The methodology explains how things should be done and allows documentation to show how things were done during the project.

Repeatability – The methodology can be repeated and the results of two or more projects can be adequately compared.

Learnability – The methodology has a structured language that is intuitive, useful, and free of vagueness. The methodology can also be interpreted naturally and similarly across the perception of all who learn it.

Applicability – The methodology should prove easy enough to adopt, and useful enough to use to break down organisational adoption barriers.

E - Usefulness

Comparing the result of using the methodology with the initial performance claim.

Efficiency – The methodology is not too resource/effort intensive for its outcome.

Effectiveness – The methodology delivers the desirable outcome for the specified acceptable uses.

F - Problem Specificity

Problem Specificity – The methodology clearly shows in which applications it works best.

G – Structure and Compatibility

Constructing the methodology in a way that is sufficient for the nature of the work and accommodates the project, the product and all its actors and information.

Handling Complexity – The methodology handles the complexity of project management as well as the product by simplification.

Problem Solving cycle – The methodology solves problems and dilutes them into a "task" state.

Structuring – The methodology suggests the most effective and efficient methods for its use.

Compatibility – The methodology is compatible with the engineering domains and their tools/techniques.

H – Flexibility

Flexibility – The methodology allows the designer to make decisions regarding methods and the ability to adapt.

Note that the aspects above are not binary (pass/fail) in terms of criteria, but are measured in degrees of success in that aspect.

2.2.4 Classification of design methodologies and approaches

Design models typically fall under one of four categories (Blessing L. T., 1994) based on their structural reliance on stages and activities. (Hall A. D., 1962) Figure 2-3 **Error! Reference source not found.**below shows a typology by Blessing, which is a refinement of Hall's work, of 4 types of design models commonly present within engineering design research and practice. The two dimensions on the axes represent stages, a chronological, morphological structuring of models with a more linear process, and activities, a cyclical, iterative structure with repeated tasks. (Asimow, 1962) In practice, the stage-based approaches are much more prevalent than purely activity-based approaches as the former are perceived as more manageable and useful. Therefore, it can be assumed that some sort of staged structuring is a critical element in methodology design. The helical device shows the iteration of activities as a cycle of improvement, the spiral shows a similar idea, but as the width of the spiral decreases, it reflects the shrinking design, solution, and creative space.

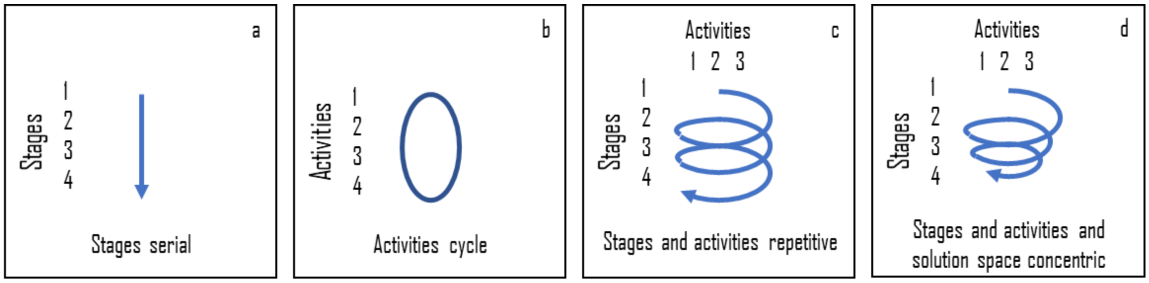


Figure 2-3 - 4 types of design models

Design methodologies can adopt general strategies that help aid the user choose and implement problem-solving strategies. Typically, stage-based models are of a problem-oriented nature, whilst activity-based models may use a problem or solution-based approach. This is the second classification a methodology can receive.

The third taxonomy for the classification of design models is based on their approach to a model. Abstract models are generic and flexible with no specific application guidance. Procedural models are more refined and solid, generally focussing on a particular project aspect. Analytical models are used to describe specific aspects of the design project and sometimes specific, tools, methods and procedures used. Abstract models are usually activity based, which is inherently abstract in nature, but may also be problem or solution oriented. Procedural models are generally problem-oriented, stage-based approaches. Analytical models fall outside of this nebulous-concrete spectrum and are not considered further for the purposes of this thesis (Wynn & Clarkson, 2005). Figure 2-4 shows a compounded classification model for design methodologies, showing 12 classifications. Depth of shade in each classification gives a rough idea of that category's prevalence within engineering models relative to each other.

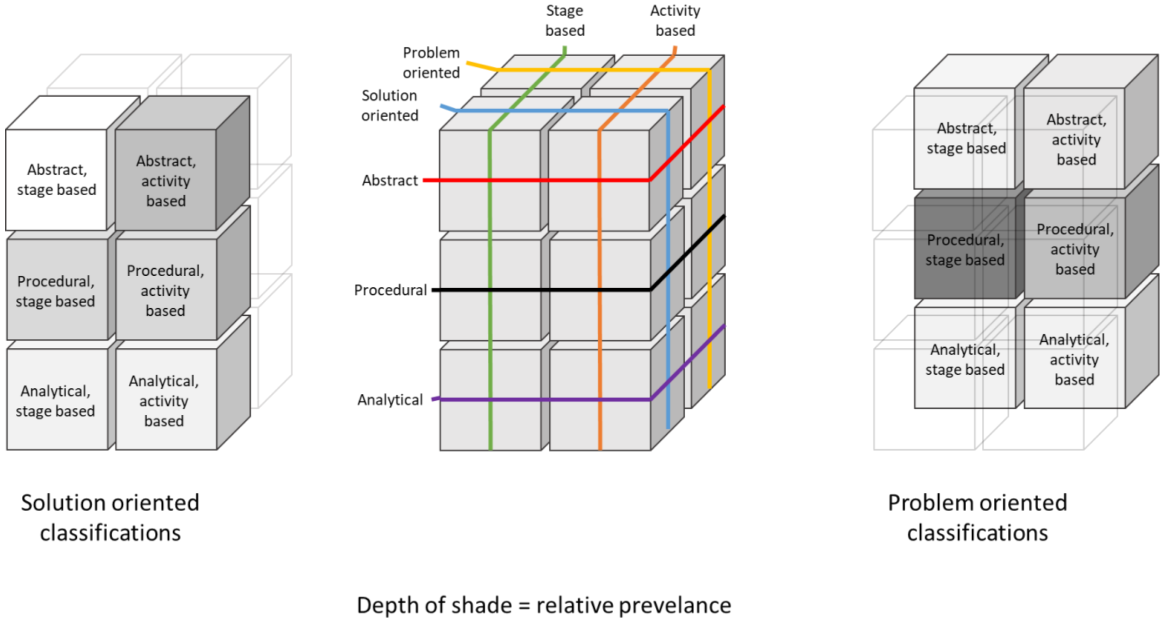


Figure 2-4 - Compound view of model classification

Engineering design, especially for complex systems, tends to use more robust, systematic models. Abstract models cannot readily accommodate the complexity required for large scale, modern systems engineering projects, where accountability and documentation are important factors. For this reason, procedural, stage-based and problem-oriented models are common. Effective systems engineering models will fall into the common categories as they will provide necessary project structure obtain effective, efficient results.

2.3 Complex systems

Complexity is inherent in system design, thus learning how to mitigate its negative effect is a key factor in methods and methodologies. Understanding what kinds of complexities there are is the first step in understanding how to beat them.

2.3.1 Defining complexity

In the design world, complexity can be explored and modelled in many ways, but is simplified by Suh's (Suh, 1999) engineering definition:

> *"Complexity is defined as a measure of uncertainty in achieving a set of specific functions or functional requirements."*

Models of complexity theory can be abstractions, much like lattice structure hierarchy (Earl, Johnson, & Eckert, 2005) which show how complexity comes from interrelation between components or functions in a product, shown in Figure 2-5. Some are categorical models following on from Suh (Suh, 1999), shown in and Figure 2-6.

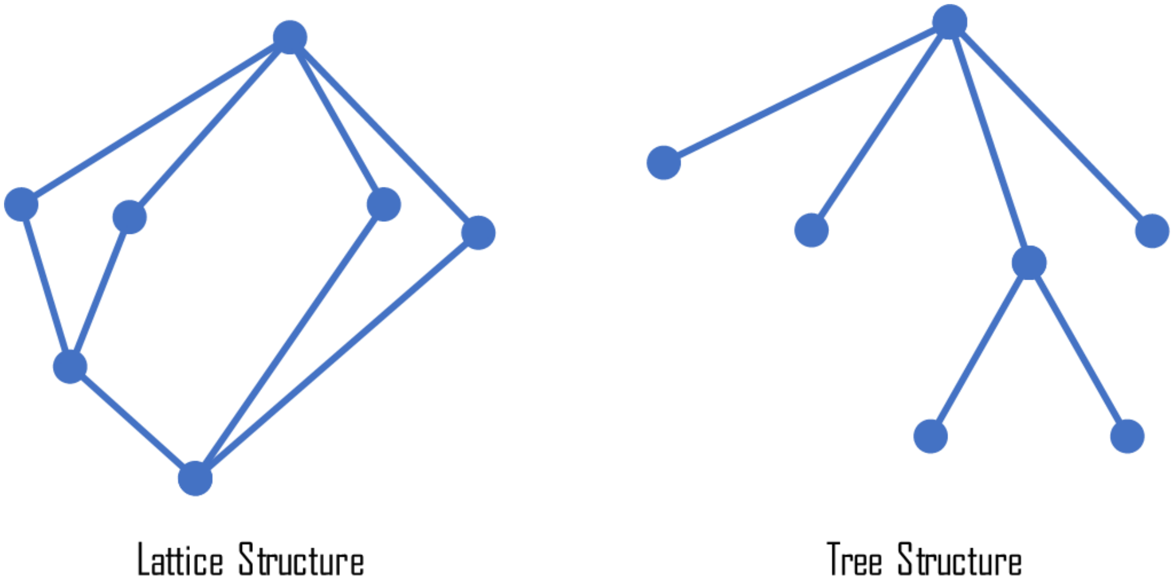


Figure 2-5 - Complex lattice structure vs traditional tree structure (Earl, Johnson, & Eckert, 2005)

The tree structure for complexity is the common representation of conventionally designed products. For example, the design of a chair may be simple enough that the functional interactions between comfort, price and affordability are directly linked, and do not have complexities within them that wildly vary the impact of a change. The lattice structure can model the interfaces between two sub-systems in a satellite for example, where large electronic devices demand greater thermal management capability, requiring more space, requiring better power management, which requires larger power, which increases thermal load, and so on. The complexity of a system is defined by the interactions between each of its elements.

Suh categorised complexities into definable quadrants, shown in Figure 2-6. Identifying what kind of uncertainty an engineer is facing allows them to tackle it. For example, Combinatorial complexity arises when several known systems are to be integrated, and the result of interactions is unknown. A strategic response to this information is to baseline and verify the five systems from low to high level.

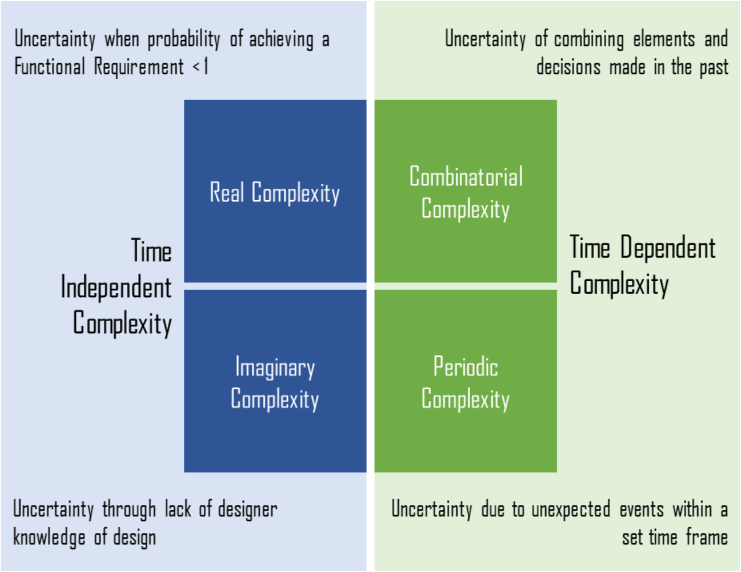


Figure 2-6 - Model of total complexity (Suh, 1999)

Both models above demonstrate the effect of complexity in the PDP. Complexity can be present in the product, process, users or engineers within the design process, and these complexities can combine, leading to a design process that is difficult to handle and a product that produces problematic emergent behaviour.

Complexity appears based on the balance between uncertainty and order , the relative difference in the balance and the order-state (constraints) is known as entropy (Jaynes, 1957). This balance changes over the design process and is predominant in the early stages. Entropic balance also varies across various system levels, such as components or sub-functional levels. Entropy can arise in the conceptual design phase; confidence in the design of the complex system may be low at this point, but confidence in the requirements works to reduce the number of viable configurations. In doing so constraints are established and uncertainty is reduced.

Complexities have types, as mapped in Figure 2-7. The x-axis is known and unknown uncertainty, the y-axis visualises uncertainty in Data or in Design.

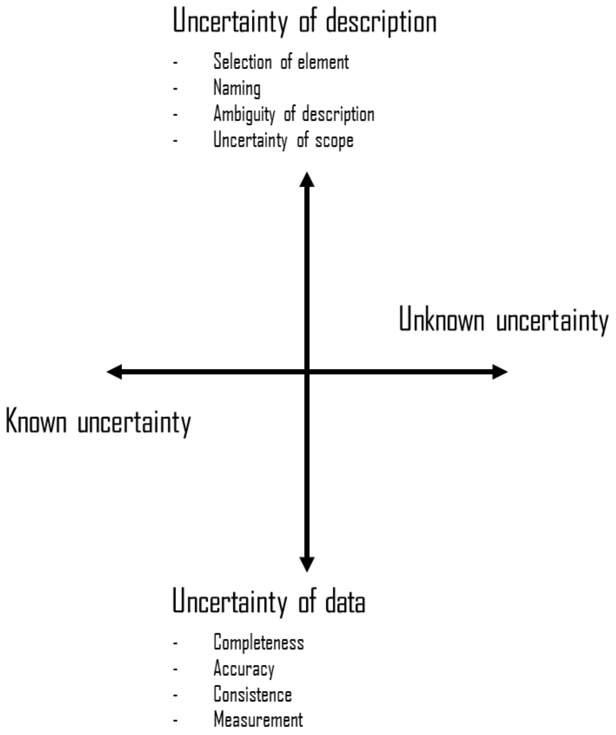


Figure 2-7 - Complexity axis

Known uncertainty is determined from previous designs, and can be estimated through experience of similar design projects. Known uncertainties are predicted problems, but the specifics of that uncertainty are not entirely known. Unknown uncertainty comes in the form of events that cannot be predicted, such as design failures or employee absence. Uncertainties of description are concepts such as component interaction, ambiguity in description and unaddressed design concerns. Uncertainty of data is due to incompleteness, inconsistency, or inaccuracy. It is important to understand these classifications of complexity as solving complexity problems first requires identification of the sources and characteristics of complexity.

2.3.2 Characteristics of complexity

Complexity in relation to design can produce unforeseen and unwanted behaviour from the design process or system (Earl, Johnson, & Eckert, 2005). By identifying the specific characteristics of complexity, one can strategize to mitigate and manage its effects.

Firstly, designs which are complex can fall victim to deterministic chaos. If the system is hard to predict it can become sensitive to minor mistakes made in the initial design phases. When these mistakes happen, the system behaviour takes a large leap towards unpredictability, and may also appear to be acting normally. (Suh, 1999)

Secondly, the interplay between sub-systems and components in a complex system does not take the form of a simple product tree, but rather a lattice structure, much like in Figure 2-5. Sub-system relationships are not as simple as parent-child, but rather interdependencies between multiple sub-systems. Events that happen in one sub-function will have knock on effects that reach beyond its immediate links in the lattice, potentially even across the whole system and even back on itself.

Thirdly, large amounts of information flow occur in the system/design process. Data, power, heat, and fluids are some transmitted components of a product, connected via interfaces between sub-systems or an underlying architecture. At the process level, knowledge, decisions, and design information are connected through organisational channels and networks. The management of information traffic through these connections is also complex.

Finally, high component and interaction counts can cause a combinatorial explosion, especially when a new part is added. This new part has direct links to its neighbouring functional components, in the typical complex lattice structure way. However, the new part may create more indirect links with other components and sub-functions that did not exist before, and with the addition of each new component the number of relations grow exponentially.

These consequences are useful to know as it helps the engineer understand the gravity of their actions when undertaking a system design. If complexity can be identified within CSE, mitigating actions can be taken. The act of determining complexity and its properties in a system or process is beyond the scope of this thesis; only the understanding of the implications of complexity and how to address them is relevant.

2.3.3 What is a “complex system”?

A complex system is an amalgamation of engineered sub-systems that come together as a single entity to perform a multi-functional role, often in the form of a large structure or vehicle containing these sub-systems. (Andrews, 1998) Complex systems are defined by traits possessed by the design and design process. Andrews determines the traits possessed by a complex system and its conception in the context of naval ships:

1. The ability to operate in a wide variety of demanding environments
2. The size of the unit
3. Long endurance and self sufficiency
4. Role flexibility
5. High level of complexity and employing diverse technologies
6. Close interdependency and high level of integration of a myriad of subsystems supporting each individual function
7. Small procurement numbers, high procurement costs and inherent long life

Complex systems have complex requirements, which affects the complexity of the design process. A complex design process on its own does not define the product as being a complex system, but it is symptomatic of a complex system to have a complex design process.

2.3.4 Complex vs conventional system design

Complex systems engineering comes with additional challenges that need to be accounted for in the engineering design process. Most of these differences stem from the increased scale and uncertainty within the project. Aspects such as increased part count and manufacturing intricacies can be accommodated. Process related differences due to budgetary or time constraints have to be explicitly addressed and engineers have to pay attention to these. Table 2-3 sets out some of the qualitative properties of conventional products, mechatronic products, and complex projects.

	Conventional	*Mechatronic*	*Complex*
Volume production	High/very High	High-very Low	Low/once
Cost per unit	Low/very Low	Moderate/high	High/very High
Project size	Small/medium	Medium/large	Large/very Large
Average quality	Low/very Low	High	Very high
Focus	Manufacturing	Product	Project
Manufacturing style	Highly automated	Automated/repetitive	Mostly manual
Project management	Linear methods	Linear methods	Non-linear methods

Table 2-3 - Conventional, mechatronic and complex projects (Melville & Yan, 2016)

Further insight into the complex system design process is gained by characterising it. Andrews (Andrews, 1998) shows how these traits are qualified using naval ships as his example. Andrews' traits to determine the nature of complex system design (naval ship):

1. Bespoke design for each new classification of system.
2. Identification of the balance of requirements for multi-functional system is difficult.
3. Many performance issues that cannot be expressed explicitly.
4. Political and socio-economic environment can have bearing on the design outcome.
5. Cost and time, in a political context, is pervasive throughout the whole design.
6. Importance of initial design, as prototyping is not possible, a "no risk" design also seems conservative.

The traits of complex systems mean that extra effort has to be performed at the design stage, especially in the formation of requirements. Work has to be "left-shifted" to develop materials early so that the later stages have a constrained baseline to work from.

2.3.5 Challenges of the complex systems industry

By compounding these features, four key challenges that the CSI faces can be categorised uniquely.

Complex design management

The data and physical output of large scale CSE projects can be overwhelming when compared to traditional systems engineering. Large capacity servers are required to manage the amount of data, but the data itself is more varied. For example, a CAD model of a satellite may contain separate models of the electronics, chassis, fixtures, mechanisms and heating elements, likely divided by sub-systems or payload. This added layer of complexity must be accounted for in the methodology and the management system. The sheer volume of files must be tracked and accounted for as well as appropriately labelled for use in a shared environment.

Complex knowledgebase

Complex systems are multi-disciplinary in nature and require a firm grasp of many knowledge bases. Tolerances may be tighter, requirements more demanding and designs more convoluted than traditional engineering. Documenting and tracking this knowledge is more important, and computer aided tools are mandatory to ensure each team is up to date with the huge amount of information, such as operating principles and design specifications. This wider range and expertise of knowledge means that specialist teams will be more common, allocating them as project resources is an additional planning complication.

Increased uncertainty and risk

As with any high budget project, the more money invested into it, the more money is wasted if failure occurs. The increased complexity brings additional uncertainty in both process and design. Hiring graduates and novice engineers may be perceived by management as detrimental to the project as experienced engineers may be expected to take the lead and perform a disproportionate amount of the work. Design teams require more information, skill within their field and agency to complete the tasks relative to that of conventional systems engineering.

Design evaluation and non-destructive testing

High budget projects generally have more freedom and are encouraged to develop working prototypes to test and validate the “real-world” behaviour of their design. However, in large scale CSE projects, the nature of the design solution is often one that cannot be wholly prototyped as cost, time and resource constraints can prevent this. In a best-case scenario, subsystems or components can be prototyped, but not full systems. If full systems are to be tested, it would be in the post-fabrication stages, thus non-destructive testing is the only way to preserve the system integrity. Reliance on simulation and on-paper calculations can be considered mandatory otherwise.

With these challenges in mind, some strategies can be composed to mitigate or address them.

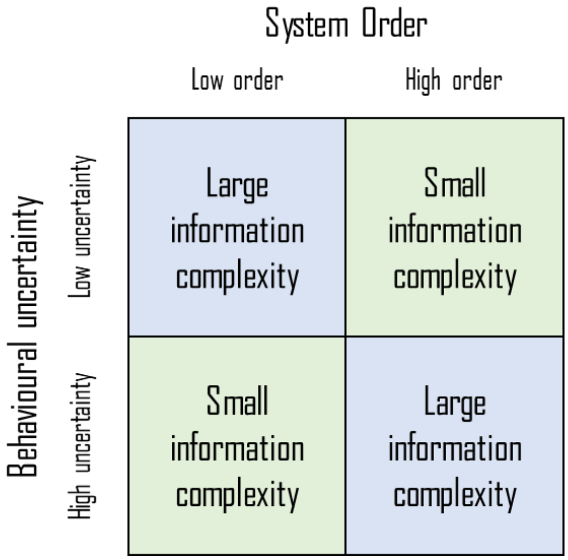
2.3.6 Dealing with complexity

There are several actions suggested in the literature that may help mitigate and manage the challenges produced by complexity in a design process or product.

Conducting regular simulations with regards to potential system states can help find a “ballpark” estimation for performance. (Earl, Johnson, & Eckert, 2005) In truth, one cannot be entirely accurate with their prediction, but simulations can produce data that suggests an acceptable operating range. Using this, engineers can shift some unknown uncertainties into the known category.

Utilising the stage-based structure of methodologies can also help mitigate product and process complexity. (Wynn & Clarkson, 2005) Gateways between stages, used to ensure that the design up to this point has been verified, can help take the complexity out of the design. When a gateway is verified, the project is baselined, and future emergent behaviour can be traced backwards to events that happened after the latest gateway event.

Another simple technique for managing complexity is to determine information complexity in a design element. One can effectively determine the complexity of a feature by its description; if a design feature or function has a short description to explain its features, it could be considered a low complexity feature, converse to a feature that requires a much longer description. This is determined by mapping behavioural uncertainty with system order, as shown in Figure 2-8.



System Order

Behavioural uncertainty	Low order	High order
Low uncertainty	Large information complexity	Small information complexity
High uncertainty	Small information complexity	Large information complexity

Figure 2-8 - System order vs behavioural uncertainty

One would assume that when a system's behaviour becomes increasingly random (high uncertainty), descriptions would inflate, but the figure describes some of these systems as having "small information complexity". This reflects the lack of knowledge surrounding the system's hypothetical state. Not much can be determined at an early stage, shortening the design description, and lowering informational complexity. It is thought that, by determining where informational complexity is present in a design, one can take actions to reduce it through the design process and thus the overall design uncertainty (Earl, Johnson, & Eckert, 2005).

The strategies described above can be implemented into tools, methods, and methodologies for engineers to use to combat complexity.

2.3.7 Methodologies for complex systems

A core difference between complex and conventional engineering methodologies is that conventional projects try to balance out manufacturability and repeatability with product quality. (Melville & Yan, 2016) In contrast, complex projects tend to spare no effort in achieving their goal, even with the use of expensive or difficult manufacturing processes, particularly where the design is a one-off. Examples of this include the Hubble Space telescope and the International Space Station.

Complex systems methodologies tend to focus on the project management aspect of design process planning. Additional consideration must be taken for the scale of the information and knowledge that is present during a project, as well as the appropriate communication channels for that information. As such, the use of Product Lifecycle Management (PLM) systems is commonplace. PLM systems manage all documentation, files and task allocations, centralised on a series of secure servers. All the micro-scale aspects of the design methodology are meticulously managed by the computer software, a development that has made complex systems a much more achievable task in the computer age. (Binz, Keller, Kratzer, Messerle, & Roth, 2011) Design methodologies for complex systems are often niche and not the focus of most design research. Some example methodologies that fall in the complex systems category are covered in section 3.3.

2.4 Industry

The complex systems industry spans various engineering and science disciplines across many functional paradigms, from commercial and private use items to military countermeasures. Automotive, aerospace, naval, defence, telecoms, heavy industry, and electronics are some of the key players that make up the complex systems industry (Miller, Hobday, Leroux-Demers, & Olleros, 1995). For example, in the UK alone, the aerospace industry employs roughly 84,000 people and contributed $21 bn annual turnover (6.4% of global turnover) in 2016 (Workman, 2017). Exports and imports range year on year due to long project lead times and overlapping completion dates. (Brien & Rhodes, 2017) Large amounts of money, even by typical engineering industry standards, are characteristic of the cost, complexity and scale of the projects undertaken in this industry. The defence sector is also a valuable gauge of CSI in the UK, accounting for 2.2% of GDP expenditure in 2016. (MOD, 2017)

All these fields are linked in their engineering complexity; however, the thesis focuses on the needs of space systems engineering. To perform that, the design process for space systems were investigated. This investigation centres around AIAA’s and NASA’s models for Product Life Cycle and takes place in section 2.5.3. The methods in space systems engineering often require the use of concurrent engineering processes and principles.

2.4.1 Concurrent engineering and iterative spiral model

Evolutions in the design process have led to the use of concurrent engineering in multi-disciplinary, complex design projects. Concurrent engineering is the parallel working of functional engineering teams operating within a shared design environment with the purpose of maintaining real-time information links. To clarify, an example diagram given in Figure 2-9**Error! Reference source not found.** shows the comparison between sequential (traditional) design, centralised design, and concurrent design. Fortescue, Swinerd and Stark (Fortescue, Swinerd, & Stark, 2011) have a poignant case with the European Space Agency (ESA) using their concurrent design facility in an early-stage design study.

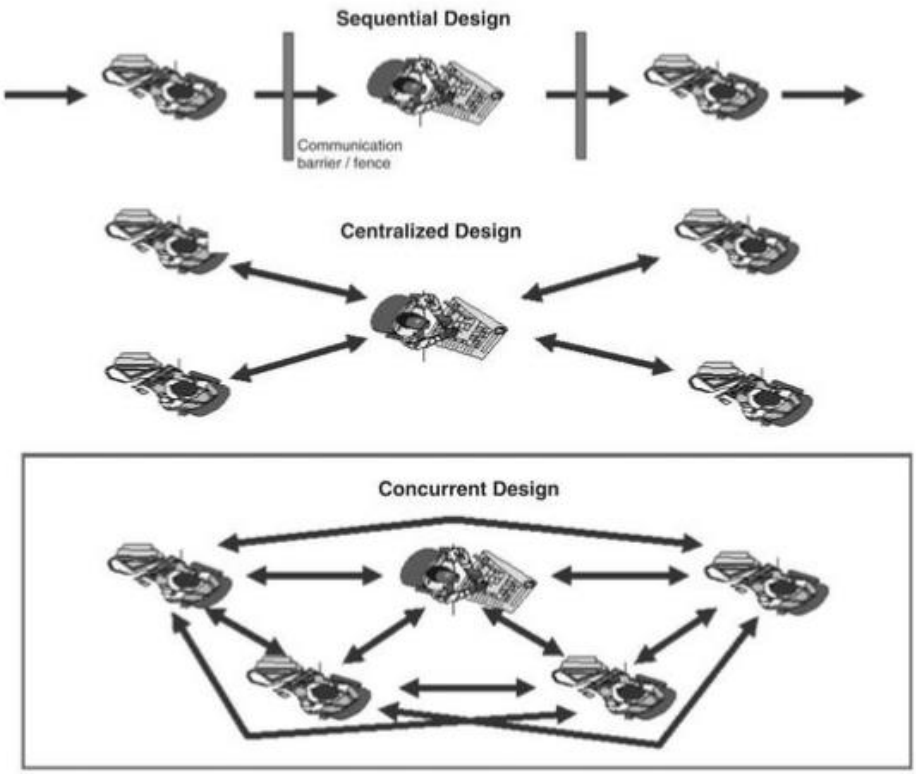


Figure 2-9 - Sequential vs Centralised vs Concurrent design (Fortescue, Swinerd, & Stark, 2011)

Concurrent design begins at the start of the design process, during conceptualisation. Using the design of a spacecraft as an example; the client puts out their Request for Proposal (RFP) and delivers some basic requirements. Using these requirements, the system designers derive specifications at a high level, communicating this to their teams. Each sub-system team will then deliberate and develop concepts to solve their part of the design puzzle, e.g., propulsion team determining which type of propulsion to use for the mission. Each team is working independently but are always aware of high-level decisions being made by the other teams and utilise this information to maintain a system perspective. This information flow is promoted through the Integrated Design Environment (IDE), using the physical space of an open office and the inclusion of a digital means of information flow. This is further supplemented using regular design meetings, the ESA call their office space the Concurrent Design Facility (CDF). These design meetings help the teams follow the evolving design throughout the process, and enable collective decision making on design changes. Once agreed upon, changes will be published and adjustments may have to be made to other parts of the design, which are captured. This is an iterative process, and one that can be visualised in the Spiral model; Figure 2-10**Error! Reference source not found.** shows a spiral model drawn in the context of sub-phases working towards evolving and finalising design parameters.

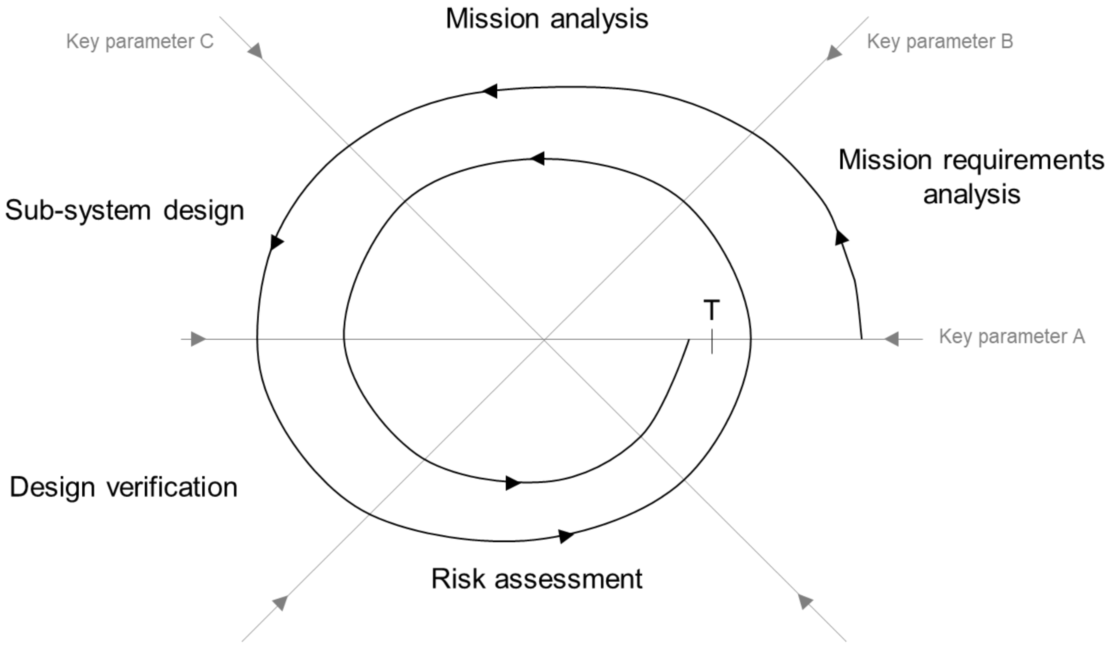


Figure 2-10 - Spiral Model (Fortescue, Swinerd, & Stark, 2011)

The spiral represents converging parameters, with each pass in a session the number of paths to a solution and the effects of a design change shrink while satisfaction of system requirements grows. To support this, it is recommended that the use of parametric modelling tools are incorporated into the process through the Integrated Design Model (IDF). This is real-time data sharing that can take the form of CAD models and documents maintained through a central information exchange. The parametric element aids the instant adjustment and update of variables, this also allows rapid testing and tweaking of new design changes.

Advantages of Concurrent Engineering

Fortescue, Swinerd and Stark (Fortescue, Swinerd, & Stark, 2011) used the case study to compare practices in CE to previous sequential engineering design processes, this highlighted some potential positives that come with adopting concurrent principles.

Firstly, the length of the study was shortened from 6-9 months to 3-6 weeks. Concurrency eliminated lengthy strings of design changes when each new change was passed "over the fence" to the next team. Instead, sub-system changes occurred through the decision of all groups and were implemented across the board in real time. On top of this, teams were always wary of the decisions being made by others and could plan for changes before they were committed. The time save allowed more studies to take place per year, academically this is good news as it reduces time and effort expenditure for validation of industry implementation. The cost of the projects was reduced by a factor of 2, indicating that the time saving aspect of concurrency directly equated to monetary savings. In addition, the working environment reduced the need for costly changes made later in the process, attributing further to the reduced effective cost. Finally, quality was markedly improved in the areas of feasibility, costing, and risk analysis. Attribution of this increase in quality was tied to the involvement of all groups in decision making, allowing all risks and issues to be considered at the meeting and not discovered post-change.

2.4.2 Changes in industry

There have been many advances in technology and technique with respect to how design engineering can be done, some of which were not around at the birth of design engineering knowledge. The most impactful of these drastic changes were the invention of the computer and the internet. These tools present both challenges and opportunities to the engineering design process and industry, the internet has connected the world without limit, bringing about an era of globalisation (Birkhofer, Feldhusen, & Lindemann, 2009). This globalisation promotes companies to invest resources in gaining and maintaining a competitive working procedure. Instead of competing with similar companies in the local area, engineering firms are now competing across the globe. This is especially true of outsourced design and manufacture; these two tasks can be done easily in two different locations with near instantaneous communication from both parties. To become relevant, design companies must work to become competitive and offer a legitimate reason for customers to be drawn to them. This is often tied in with the effectiveness and efficiency of a company’s design process: a shorter time-to-market and more efficient use of resources lead to cheaper and quicker designs.

To unlock the potential of these benefits, engineering organisations cannot rely on the experienced few to carry all the work, they have to train new experts.

2.4.3 Needs of the novice designer

As with any design company, the veterans of the design team tend to lead the team, often making decisions, answering queries and resolving problems. Ahmed-Kristensen and Wallace (Ahmed-Kristensen & Wallace, 2004) discovered through their experimentation that during some engineering tasks, novice designers knew roughly 35% of what they needed to know. Relevant queries were made around one third of the time. A further 29% of their queries showed that they knew the correct topic but not the precise information required. The authors conclude that a “question-based” method for feeding novice designers with key information will go a long way to help them.

2.4.4 Acceptance of academic models into practice

In general, application of academic methodologies and models in industry is considered “low” despite the great gain in efficiency and effectiveness that design methodologies have already brought to the industry. (Binz, Keller, Kratzer, Messerle, & Roth, 2011) Several factors are to blame for this lack of adoption, mainly the perception industry has of these methods and models.

Some common misconceptions of methods are that they are too complicated or require too much time and effort to implement into an organisational culture. Worse still, if implementation is half-hearted, it can lead to incorrect method execution and poor results. Birkhofer et al. (Birkhofer, Jansch, & Kloberdanz, 2005) expand upon this, adding that industry is still structured in their work despite a perceived lack of uptake in academic methods, likely due to the adoption of customised methodologies that “feel-right”. The authors speculate that the path from academic model to industry adoption is not fully known or set. The authors provide a Venn diagram outlining the types of design methods in use on a supply-demand-application axis, shown in Figure 2-11.

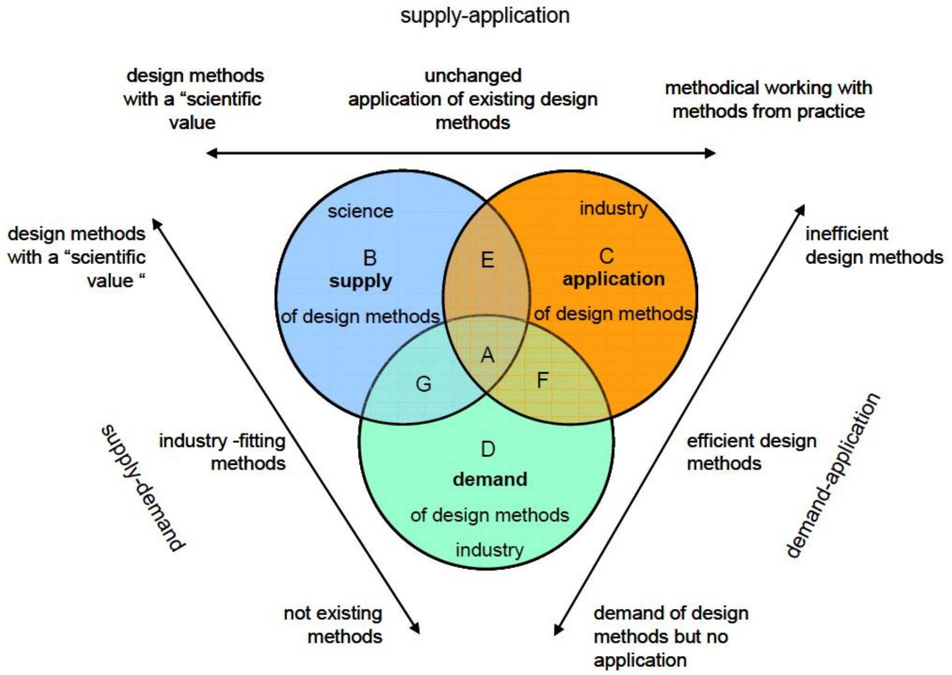


Figure 2-11 - Scheme of supply, demand, and application of design methods (Birkhofer, Jansch, & Kloberdanz, 2005)

The authors suggest that there are overlaps in methods that the industry wants (demand), the industry uses (application) and the industry gets from academic sources (supply), represented by the regions D, C and B respectively. Methods in the B range are purely academic and have no application or need; this is the worst-case scenario from an academic perspective. The ideal scenario applies to methods that fall under category A, which come from academia, fulfil industry demand, and are ultimately picked up and applied within industry.

The "demand" from industry can take the form of a desire to improve processes, decreasing cost/lead time, increasing performance/efficiency, or settling another niche challenge that industry has use for. The "application" is more nuanced, as not all methods that are demanded and supplied are implemented. This is likely to do with adoption barriers, which are the perceptions that individuals and management have on these models, often highly subject to organisational or economic limitations. The methods in category G fit into the above scenario; supplied by academia and satisfying the needs of the industry but are not implemented. These methods are often too complex, hard to understand, or require too much effort to implement.

Without relevant performance data, industry has very little reason to believe that the effectiveness of the model is as promised, this information is difficult to obtain in a sterile academic environment.

The authors concluded that the main research opportunities are to discuss and identify industry needs and satisfy these needs with adapted or optimised methods. Breaking the adoption barriers through presentation of a method's "usefulness" is also an important factor, whether the draw factor is the method's ease of use, or its effectiveness in a particular situation.

2.5 Space environment

The success of a spacecraft is dependent its tolerance to environmental conditions, accomplished through intelligent design. To understand how to do this, the traits of the common environment, space and Earth orbit, must be analysed.

2.5.1 Orbits

An orbit can be any curved path that centres around a fixed point. Orbits can be circular but are mostly elliptical and the orbit point does not have to be in the middle of the path, like Figure 2-12.

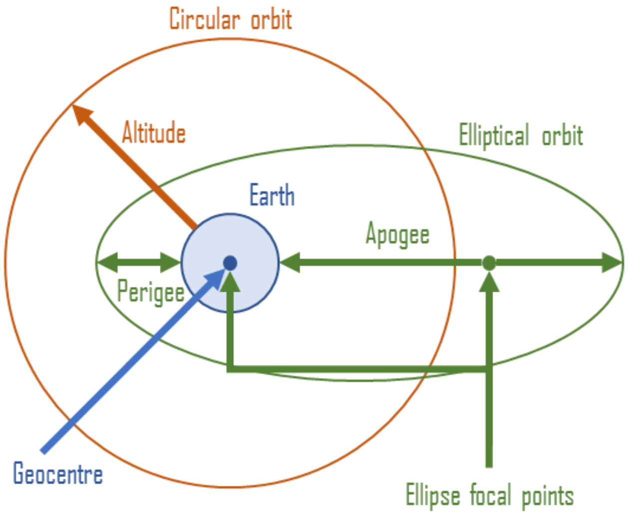


Figure 2-12 – Examples of circular and elliptical orbit types

Orbits also have an inclination, which is the angle of the orbital plane relative to the centre-point or central object, as shown in Figure 2-13.

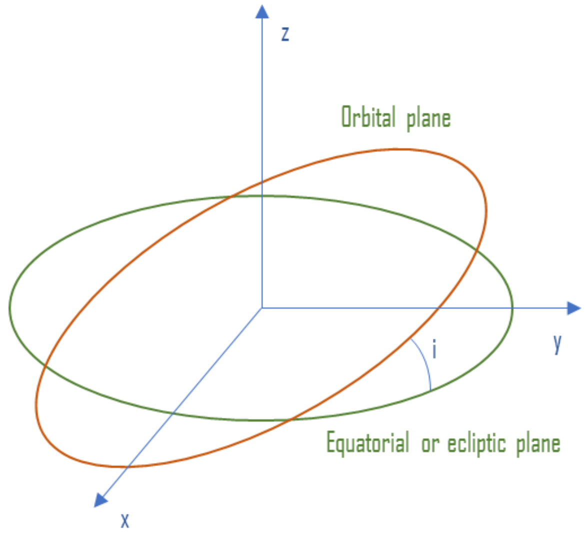


Figure 2-13 – Orbital Inclination

Low Earth Orbit

A Low Earth Orbit (LEO) is between the altitude of 180 and 2000 km. This orbit is typical of military and weather observation satellites as they are close enough to the ground to observe details.

Medium Earth Orbit

Navigation satellites tend to populate the Medium Earth Orbit (MEO) region, which is between 2000 and 36000 km.

Geosynchronous Earth Orbit

In order to orbit the Earth at the same speed of rotation, satellites need to sit in Geosynchronous Earth Orbit (GEO) which is about 36000 km or more from the surface. Satellites here can observe the same spot on Earth at all times, which is very useful for communications satellites. (Brown & Harris, 2018)

Below in Table 2-4, a comparison between Earth and orbital environment is shown, concluding that orbiting spacecraft are exposed to extreme temperature fluctuation, large amounts of radiation and near-zero atmospheric pressure.

Conditions	*Earth*	*Space (Earth orbit)*
Atmospheric pressure (Pa)	101300	10^{-14}
Temperature range (^{0}C)	-89 – 58	-270 – 150
Gravity (ms^{-2})	9.81	9
Annual cosmic radiation (mSv)	0.4 – 120	150 – 510

Table 2-4 – Earth vs. LEO Environment (NOAA, 2018)

The temperature of objects in space is dependent on the emissivity and absorptivity of the material; the vacuum of space does not allow heat dissipation through convection. Therefore, the only heat loss will be from radiation and conduction and individual object temperatures will vary.

When objects perform a circular orbit around the Earth, their altitude is consistent. This is not because LEO is a zero-gravity environment, but rather it is the symptom of Newton's cannonball effect. The orbiting mass is moving fast enough that the Earth is curving away at the same rate as the object is falling, shown in Figure 2-14.

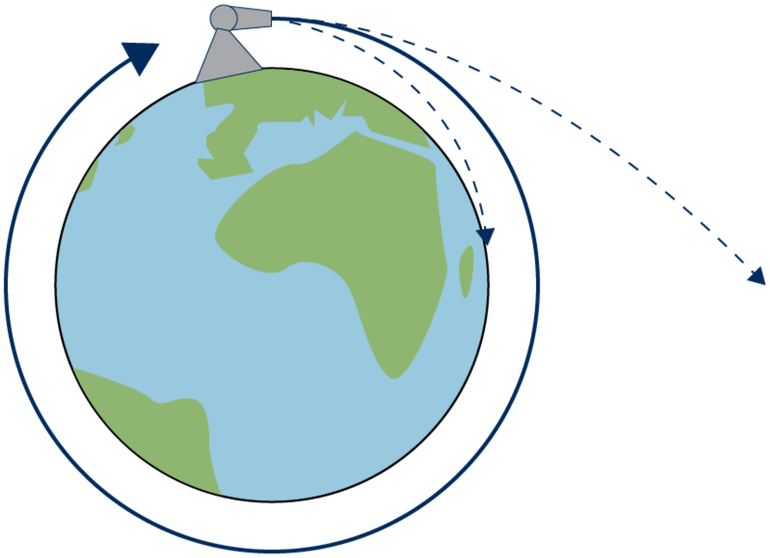


Figure 2-14 – Newton's cannonball

If the cannonball is too slow it will fall to the ground, shooting it too fast will result in it escaping the gravitational pull of the Earth. The velocity for the orbit radius must be just right for it to fall due to gravity as fast as the Earth is curving away underneath the cannonball. (Ellery, 2000)

This means that objects launched into space need to be controlled with such precision that they can orbit correctly.

2.5.2 Environmental aspects

Space environment is different to that of Earth in several ways such as temperature fluctuations, vacuum, radiation and so on. This ultimately changes the way spacecraft and satellites are designed, dictated by the extremity of the environment the system will inhabit. (American Institute of Aeronautics and Astronautics, 2003)

Hard vacuum

Air pressure is absent in the vacuum of space, and although engineers can test their designs pre-launch, it is impossible to recreate a space-perfect vacuum on Earth laboratories. This extreme vacuum can have severe effects on various materials commonly used in engineering.

Outgassing

Firstly, polymer materials can outgas, releasing trapped volatile components. These are usually lubricants, adhesives, sealants, and other volatile products used in material processing that have turned gaseous. (Cova Scientific, 2016)

Outgassing is induced through heat and moisture over long periods of time, chemical properties of the material also affect this. The compounds emitted can condense on nearby surfaces, including equipment and electronics. This poses an issue, considering that most of the instruments on board a spacecraft or satellite are sensitive. The solution to this is to be selective with the materials that are used in aerospace applications, specifically considering low-outgassing polymers and adhesive.

Metals

Secondly, certain metals can have several problematic behaviours in a vacuum, such as cold welding and relocation of plating materials. Cold welding occurs when two metal surfaces of similar elemental composition are connected in a vacuum and fuse together. This is caused by the absence of an oxygen layer on the metal surface, pulled off in the vacuum. The atoms in each metal have no distinction between items so bond freely on the other surface. Plating metals may also re-condense on cold areas of the metal. (Johnson, 1994)

The final challenge vacuums pose is the lack of convective heat transfer. This poses some thermal implications for spacecraft with sensitive payloads. Workarounds are planned via the thermal control design of the craft and material choice; opting for materials with low expansion coefficients will alleviate any tolerance issues.

Radiation

Radiation can pose a problem for electronics on board craft; however the main threat is to manned missions. The effects of radiation can range from minor electronic problems to potentially fatal radiation sickness. Radiation comes from three primary sources.

The first is from cosmic rays, high energy atomic nuclei originating from deep space, mostly due to supernovae. These particles are infrequent, but their high energy makes shielding against them impractical. The rarity of cosmic rays makes the radiation dosage acceptable, but it is possible for a single event upset to be severe, as evidenced by STS-31’s RAM malfunction. (Bedingfield, Leach, & Alexander, 1996) Long term exposure can also be a health risk for crews; thus, these rays are considered a barrier to crewed missions and deep space travel. (Cucinotta & Durante, 2006)

Another source of radiation is directly from the Sun, which has high energy emission events called solar flares. These emit high energy particles that are a health risk for humans long-term but aren’t a risk to electronics. These particles are lower energy and more common than cosmic rays, thus shielding for them is quite possible. Shielding of 2-4 g/cm^2 works for common events, 10g/cm^2 works for rare high energy events.

The final source of radiation emissions is perhaps the most critical, radiation belts. Earth is surrounded by the Van Allen radiation belt. The belt is made up of charged particles trapped by Earth’s magnetic field and causes problems for both crew and equipment.

Particles, plasma, and charging

In LEO, the first few hundred kilometres above sea level has a risk of particle charging. This altitude of orbit has a few issues to consider during space system design.

Spacecraft charging can be caused by numerous events while passing through LEO, namely:

- High spacecraft velocity through plasma
- Electron flux
- Solar ray effects on plasma in orbit
- Contamination of spacecraft surface and in the neutral plasma environment
- Generation and emission of plasma and electromagnetic radiation

(IASB, 2018)

There are many ways to classify spacecraft interactions with plasma, but in general the interaction generates charge, leading to an assortment of problems. Erosion and surface damage to the craft can occur, electrostatic discharge and electromagnetic waves can be generated, offsetting or even destroying sensitive measuring instruments on-board. Smaller spacecraft fair better in this regard as they collect fewer ions to the electron. The photoemission effect also helps discharge the craft.

Oxidisation proves to be a surprising issue; in deep space corrosion is not a problem, but in LEO environment oxidation can occur. The oxidation comes from atomic oxygen, which makes up 95% of LEO atmosphere. (Pippin & Bourrasa, 1995) Metals such as silver and osmium have very strong reactions, and other common metals can react without some surface protection. Bare, untreated metals will suffer oxidation, but some surface coating or other protection will prevent this. This atomic oxygen can also affect polymers, with oxidisation and ablation occurring on the surface of many polymers. (Hansen, Pascale, De Benedictis, & Rentzepis, 1965)

Meteoroids and debris

Impact of debris and large particles in space is a frequent risk to objects in orbit. In orbit most instances of collision are cause by meteoroids and man-made spacecraft debris.

Meteoroids are small bodies, usually pieces from comets (icy-rock) or asteroids (stony-iron); travelling at high speed through the solar system. Size ranges up to a meter, the larger side of the spectrum is rare and anything smaller than a few centimetres is considered a micrometeoroid. Most of the damage caused is pitting and sandblasting on spacecraft exteriors, thus ships like the ISS need to be armoured to protect itself from these common encounters. A near-comet environment is particularly dangerous and being in near-planet environment increases the density of meteoroids while shield spacecraft from them. Being in Earth's orbit also has its own challenges due to man-made debris.

Man-made space debris, from decommissioned, failed and partly destroyed satellites is a growing problem in the Earth orbit environment, particularly in LEO. Most fully intact satellites can be tracked and thus avoided via craft manoeuvres. Small debris like panels, bolts and other fixtures cannot be tracked. These are caused by explosions or collisions with other satellites. These types of debris cause the most damage, armouring for them is a massive weight penalty. (NASA, 2010)

The environmental aspects are part of the key differences in space systems engineering compared to terrestrial product design. For this, and several other reasons, space system design processes differ from traditional engineering processes.

2.5.3 Design phases of spacecraft

AIAA's determination of design phases for spacecraft/aerospace design is used to establish a general overview of the design tasks required. (American Institute of Aeronautics and Astronautics, 2003) Complex systems design is markedly more structured than the intentionally vague fundamentalism of the design process envisioned by academics. This structural rigidity is reflective of the design management processes crucial to project success. Below, the typical design phases for spacecraft are listed and explained.

Phase A

Phase A of the spacecraft design process is the feasibility analysis, which is triggered by the issue of a Request for Proposal. Phase A involves receiving and developing the customer requirements into specifications, performing high level conceptual design of the system, and projecting project parameters, such as cost, timescale, and resource requirements. (The Rover Team, 2006) This phase lasts 8-12 months and is not costly relative to the overall project, but is considered the most critical, as most major high-level decisions are determined within this phase.

The first key component of the phase is to evaluate conceptual solutions to the mission problem. Suitability of these solutions is determined by their ability to adhere to specifications efficiently and effectively. (Mosher, 1999) Specifications are derived from the customer's input; mission, launch and payload requirements are iteratively improved. Next, the design is demonstrated as a candidate for the mission through initial design analysis by referring to past designs, employing computer analysis on critical components and utilising research. Finally, the definition taken forward to phase B is defined and agreed upon in a Preliminary Requirements Review (PRR) at the end. This review judges the readiness of the conceptual design moving forward and acts as a milestone for agreements regarding design decisions such as sub-system functionality. Sometimes the documentation of this phase can be part of a proposal to an open invitation for mission design, approval then allows Phase B to go forward.

Phase B

After the conceptual design has been approved, the design must be realised. Phase B covers the detail development stage of the design process where concepts are refined and components, dimensions and manufacturing requirements are specified. This section of design may last 12-18 months but possibly more.

From the beginning of this phase, the sub-functional requirements are developed, evolving the system requirements document from Phase A into a much more detailed version, which helps constrain sub-system design teams. This is followed by the System Requirements Review (SRR), which seeks to check that the specifications developed thus far align with the initial customer's requirements. Then follows the low-level design for subsystems; sizes, materials and other quantities are defined. To avoid troublesome "over-the-wall" design, teams work concurrently. The process is lengthy, so long-lead items are identified and ordered at this point. The System Design Review (SDR) is also carried out, which evaluates the overall design with respect to the requirements. This is also used as a milestone target for shifting to the next phase. Independent reviews by the customer may also be carried out here.

Phase C

Following the detail design, Phase C covers the finalisation of designs, their analysis and preparation for manufacture. The Preliminary Design Review (PDR) should be complete before the design is taken to issue, and the Critical Design Review (CDR) should be done pre-manufacturing. All manufacturing processes should be ready to go on delivery of the design drawings.

Phase D

The final design related phase in the process is the fourth phase, which covers the manufacturing, sub-system assembly and testing as well as combined system testing. Phase C and D combined make up the longest element of the project timescale and can last anywhere between 3 and 5 years, even longer if there are setbacks. Sub-system testing involves the checking of all components before being assembled into their sub-system for their independent functions to be tested, this is the basis of the Test Readiness Review (TRR). Once these are complete, sub-systems are assembled to make the whole system, which is tested. If all checks out satisfactorily, then the Flight Readiness Review (FRR) is complete. If sub-systems are brought together for the first time at the launchpad, the FRR review is either held then, or accommodated earlier in the process by the TRR. Computational elements that can be tested pre-assembly should be.

Phase E

Phase E is the operational phase of the spacecraft, which includes the launchpad assembly, Launch and Early Orbit Phase (LEOP), and mission commencement. LEOP includes the launch of the craft, orbital manoeuvres, deployment of arrays, equipment activation and initial system tests. It is usually in this phase that ground operators discover issues in the spacecraft’s function. It is important to perform these post-launch tests, as some software issues can be patched. Disposal and decommissioning also need to be considered, as they are part of the contractor’s agreement to handle the removal of the craft once its mission is over, usually in the form of de-orbiting. On-Orbit servicing (OOS) is also considered part of Phase E if it is deemed necessary for the craft.

This phase layout looks like a traditional design process on the surface but has a few notable differences. This kind of process is heavily documented and internally supervised; scheduling is conducted earlier on in the project as per traditional design, but the timescale is much grander. Each work segment is categorised into phases, and these phases are gated with reviews, used as verification checkpoints. This kind of technique is invaluable to lengthy projects, as it “reality checks” the process, ensuring mistakes are caught earlier rather than later. This drives down cost of design change.

Like the AIAA process is the NASA space flight product lifecycle, shown in Figure 2-15. This process is taken from NASA's set of standards, NASA Procedural Requirements (NPRs). NPR 7120.5 contains information on the projected product life cycle, showing key review points.

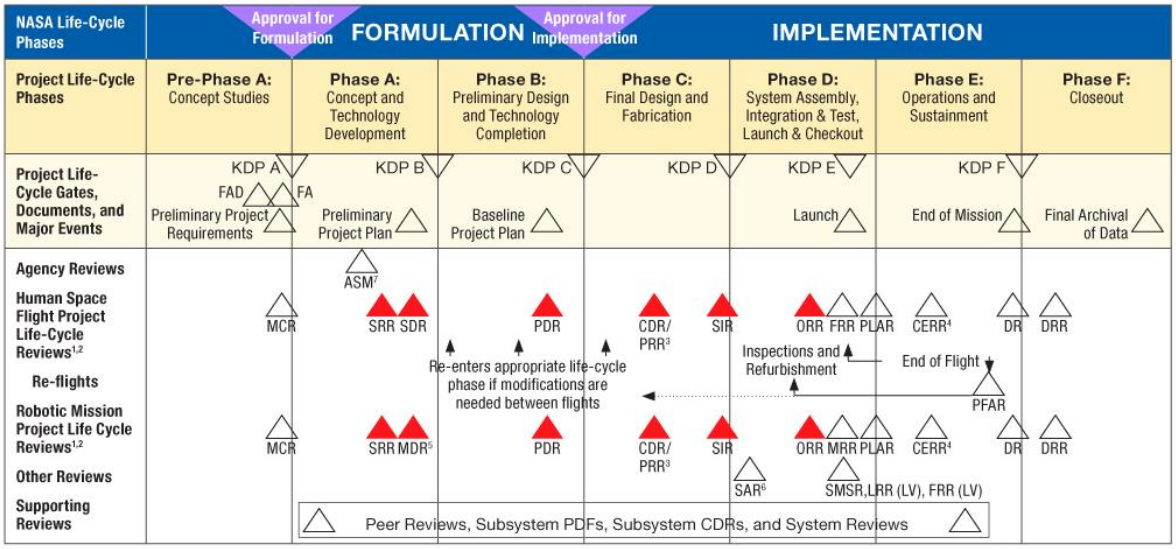
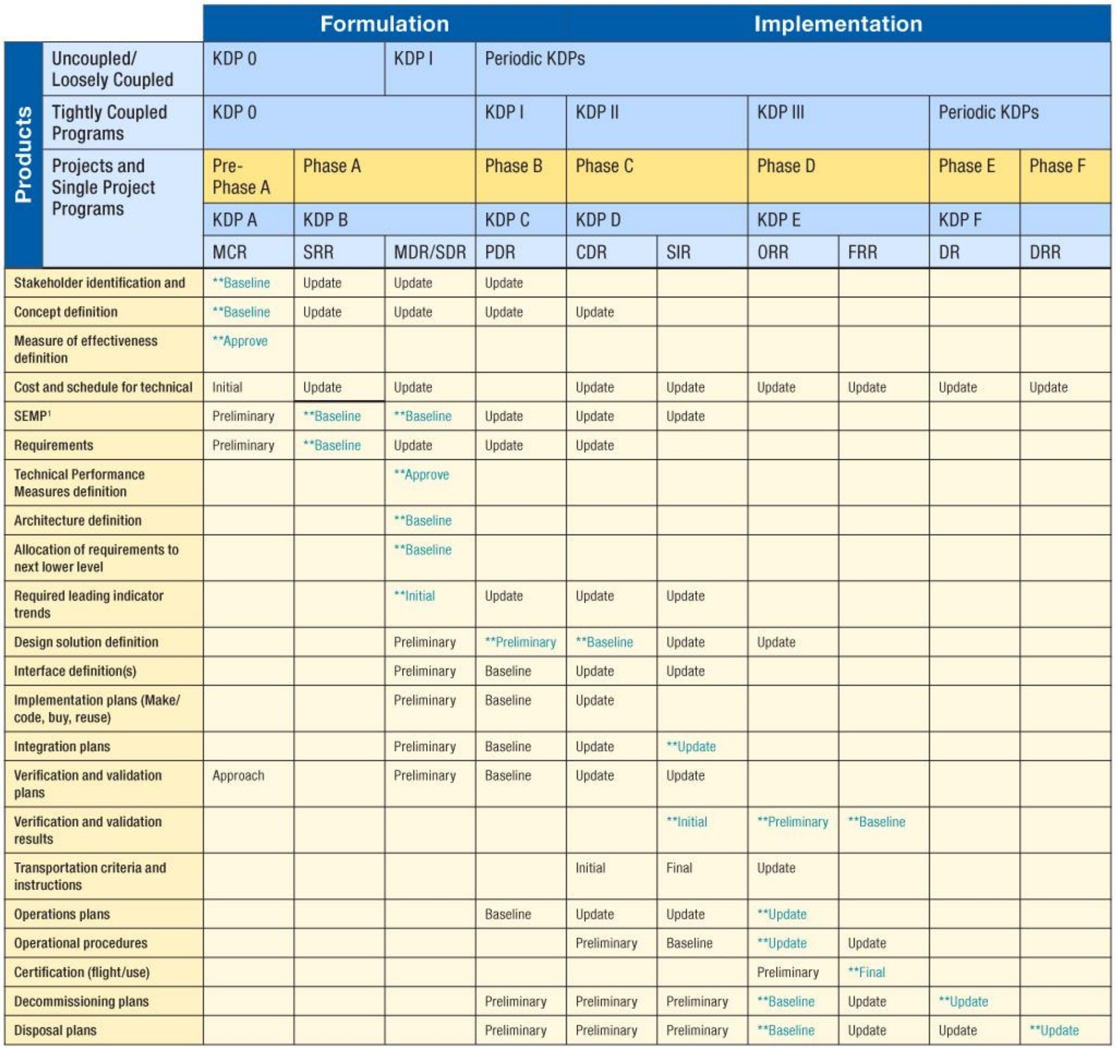


Figure 2-15 - NASA Space flight Product Life Cycle

The core similarities of the two processes come from the commonalities in the phases, timescales and Key Decision Points (KDPs). KDPs are the critical decision making points to allow current progress or change it. These act as gateways between each of the phases. The type and timing of the review is not critical, but rather that the information being reviewed in that point in time is relevant to the continuation of the design process.

One of the main benefits of the NASA cycle is their adherence to documentation and actions across the design process, and how these should be tracked. Figure 2-16 shows what the expected documentation is for each stage and review within the design process. This is invaluable for the system engineer, as it allows management of resources to ensure deliverables are met on time and to the expected useful quality.

These two life cycle processes are similar because many of the optimisations in the field of systems engineering have coincided with this kind of approach. The scale and complexity of space systems demands a process that controls progress very tightly, as the product risks lives.



Products	Formulation				Implementation					
Uncoupled/ Loosely Coupled	KDP 0		KDP I	Periodic KDPs						
Tightly Coupled Programs	KDP 0			KDP I	KDP II		KDP III		Periodic KDPs	
Projects and Single Project Programs	Pre-Phase A	Phase A		Phase B	Phase C		Phase D		Phase E	Phase F
	KDP A	KDP B		KDP C	KDP D		KDP E		KDP F	
	MCR	SRR	MDR/SDR	PDR	CDR	SIR	ORR	FRR	DR	DRR
Stakeholder identification and	**Baseline	Update	Update	Update						
Concept definition	**Baseline	Update	Update	Update	Update					
Measure of effectiveness definition	**Approve									
Cost and schedule for technical	Initial	Update	Update		Update	Update	Update	Update	Update	Update
SEMP[1]	Preliminary	**Baseline	**Baseline	Update	Update	Update				
Requirements	Preliminary	**Baseline	Update	Update	Update					
Technical Performance Measures definition			**Approve							
Architecture definition			**Baseline							
Allocation of requirements to next lower level			**Baseline							
Required leading indicator trends			**Initial	Update	Update	Update				
Design solution definition			Preliminary	**Preliminary	**Baseline	Update	Update			
Interface definition(s)			Preliminary	Baseline	Update	Update				
Implementation plans (Make/ code, buy, reuse)			Preliminary	Baseline	Update					
Integration plans			Preliminary	Baseline	Update	**Update				
Verification and validation plans	Approach		Preliminary	Baseline	Update	Update				
Verification and validation results						**Initial	**Preliminary	**Baseline		
Transportation criteria and instructions					Initial	Final	Update			
Operations plans				Baseline	Update	Update	**Update			
Operational procedures					Preliminary	Baseline	**Update	Update		
Certification (flight/use)							Preliminary	**Final		
Decommissioning plans				Preliminary	Preliminary	Preliminary	**Baseline	Update	**Update	
Disposal plans				Preliminary	Preliminary	Preliminary	**Baseline	Update	Update	**Update

Figure 2-16 - NASA required actions per design phase

2.6 Verification and validation

One of the major challenges with space-faring projects is the lack of traditional testing. System tests must be non-destructive in nature, lest the system be damaged. Alternative means of providing confidence in the design are through the employment of Verification and Validation (V&V) techniques in the design process.

V&V are well explored fields in the context of engineering; their basis in empiricism allows these realms to intertwine flawlessly. The challenge lies at the design side, where discrete values are often not the key to "success" and qualitative aspects are given more weight.

2.6.1 Verification vs validation

It is important to note the difference between these terms. Verification and validation are two independent concepts that work together to ensure that the product will fulfil its function properly. The difference in these concepts is important and can be summarised in this statement:

> *"Validation checks that you're building the right product, Verification checks that you're building the product right."*

(Easterbrook, 2010)

Verification checks involve mapping the activity or task performed to the system requirements and project plans. It is an internal evaluation process that can be done at the preliminary stages of the design. Within the realm of design engineering, ISO 9001 defines the verification process as one that ensures that the design has addressed each of the specific requirements as set by the design specification before the product is delivered. Whether the design proves that it satisfies said requirements is the validation component. ISO 9001 blog (Hammar, 2018) describes verification best as "strictly a paper exercise", comparing design outputs with requirements. In doing so, engineers can determine if all requirements have been reflected in the design and documentation. Verification is not entirely useful to the end user, for so long as their product functions correctly and well, they are not concerned for the process undertaken to deliver it.

To "Verify a design methodology would incorporate benchmarking the documentation from that methodology alongside existing, comparable methodologies. In doing so the requirements that were planned for can be verified on paper, ensuring the methodology has a scientifically defensible structure.

Validation will check aspects of the process by referencing them to the original design problem or need. Validation is:

> *"confirmation by examination and provision of objective evidence that the particular requirements for an intended use are fulfilled." (FDA, 1997)*

As stated previously, validation is assurance that the product is an efficient and effective means of delivering the desired output. This means that validation occurs as the result of the output and can be directly measured by the customer's satisfaction. This requires post-product analysis and case studies to gather data, such as product satisfaction surveying. This can then be compared to the initial design requirements to establish how well the design satisfies them. If the product meets established milestones in satisfaction, then the product can be considered valid.

In terms of design methodology, this step can only the design is finished. Case studies and direct feedback from designers can help establish the degree of success of the methodology.

Verification is a question of maximising the chance of success to deliver the validated product by checking the interim development steps. If each step in the design process was undertaken correctly, then it can be assumed that the design is valid. This jump between verification and validation is a "leap of faith" based on a series of checks and assumptions of correctness.

System verification is modelled in simplistic terms in Figure 2-17, and in Figure 2-18 it is expanded into something called the V-model. In short, these two models depict a simplistic overview of the design process that shows the development of validation protocol and requirements in parallel with the sub-system design. The later part of the design process uses these criteria to verify and validate the design.

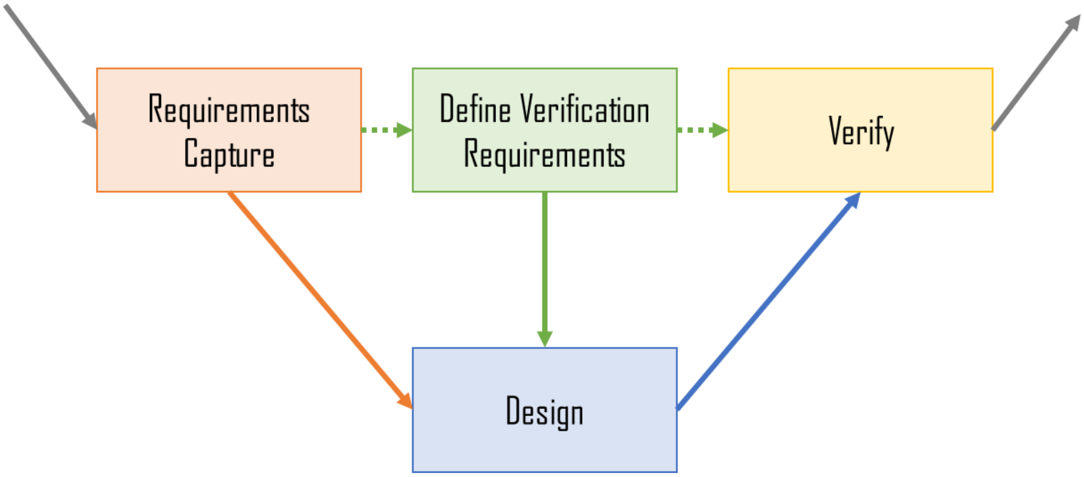


Figure 2-17 – Generic verification model from design verification (Alexander & Clarkson, 2000)

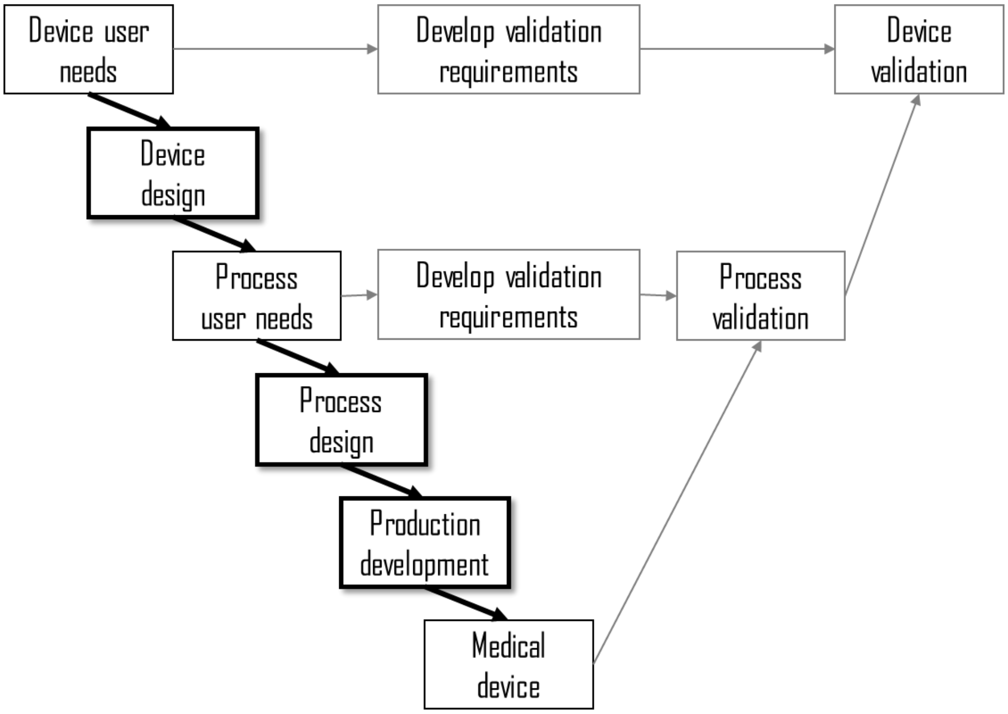


Figure 2-18 - System validation (Alexander & Clarkson, 2000)

2.6.2 Method and methodology validation

Validation techniques for design methodologies is underused in research. Often, research will be developed to address a specific issue or accommodate a particular niche of design. Their case studies are often not followed up by a robust statistical analysis, nor a comparative benchmark based on the literature. In this sub-section, an existing research tool is discussed that assists in this endeavour called the Validation Square.

The Validation Square (V-Square) shown in Figure 2-19, proposed by Bailey et al. (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000) is a pre-validated evaluation tool specifically designed for engineering methods.

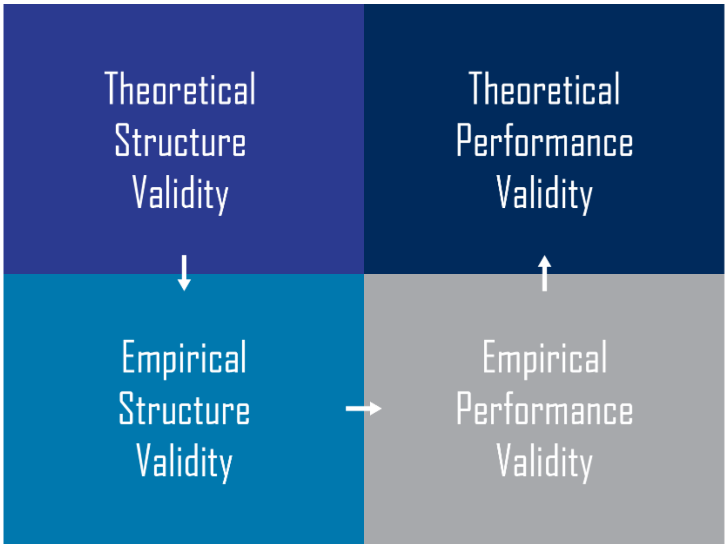


Figure 2-19 – Building confidence in usefulness and the Validation Square

V-Square works on the basis that design methods are developed to be “useful with respect to a purpose” and have been designed to fulfil that purpose. V-Square operates based on a process of determining validity and verification from a multi-perspective standpoint; it evaluates the efficiency and the effectiveness of the method based on a relativist school of thought across two dichotomies. These axes are the Structure – Performance axis and the Theory – Empirical axis.

Structure – Performance

The structure – performance axis represents the qualitative and quantitative designed aspects of the method to be evaluated.

Structural

The structure of the model represents the founding principles, process, and components of the method. For the structure of the method to be considered valid, it must be proven as “effective”, meaning that the structure is built with the intended goal in mind.

Performance

The performance of the method represents optimization, ease of use and timeliness of the method. For the performance of the method to be considered valid, it must be proven as “efficient”, meaning the performance is timely, practical, and cost considerate.

Theory – Empirical

The theory – empirical axis represents the school of thought used to validate and verify the methods. The reasoning for approaching the problem with two different schools of thought is to strengthen the validity of the validation itself.

Theoretical

The theoretical perspective of the V-Square is representative of the relativist school of thought, a somewhat subjective and qualitative look at knowledge. Concepts that are imprecise and heuristic in nature can have a relativist perspective applied to them.

Empirical

The empirical perspective of the V-Square is representative of a rationalist-empiricist school of thought, a purely quantitative look at knowledge. Concepts that are numerical and precise can have an empiricist perspective applied to them.

By validating the structural and performance aspects of the method in both theoretical and empirical means, one can obtain a broader and more robust evaluation.

Evaluation of each element through both schools of thought gives the model 6 evaluation strategies broken into four steps. (Seepersad, et al., 2006) When using the V-Square, the evaluator will action these steps, and satisfying their requirements will gradually increase confidence in the method.

Theoretical Structure Validity (TSV)

This stage focuses on building confidence in the principles and structure of the method logic. Literature, theory, and logical derivation are the main tools to achieve acceptance.

Step 1. Accepting the construct's validity

This is a theoretical analysis of the process steps and other internal workings of the method. The goal is to determine the acceptability of the basic structure with respect to the context. Literature review and expert opinion are ideal confirmation tactics for this evaluation component.

Step 2. Accepting method consistency

The main task in this step is to test that the method is internally consistent and that its input-output logic is feasible. A flow chart is recommended with the inputs and outputs of each step. Checking for redundant or useless information is also done here, usually against expected outputs determined by experts, literature, and simple logical extrapolation.

Empirical Structure Validity (ESV)

Step 3. Accepting the example problems

Accepting that the example problems are adequate can be completed in three steps:

- Showing that the example problems are acceptable for the constructs of the method
- Showing that the example problems represent the intended problems for the method
- Showing data from the example problems that support a conclusion of suitability

Empirical Performance Validity (EPV)

This stage focuses on a more quantitative analysis of the method, measuring the outcomes of performance testing. Case studies and experimentation are the main tools within this category.

Step 4. Accepting usefulness of the method for some example problems

Testing the method on the example problems and determining if the output is the correct output required. Effectiveness and efficiency are not scrutinised at this point.

Step 5. Accepting that usefulness is linked to applying the method

Benchmarking the method against other methods, or against no formal method, can help determine if usefulness is linked to the use of the method and its constructs. Eliminate as many outside variables as possible when establishing the study procedures.

Theoretical Performance Validity (TPV)

Step 6. Accepting usefulness of method beyond example problems

One must first demonstrate the previous steps, those are:

- **Show the construction of the method is meant for the example problems**
- **Show the construction of the method is consistent**
- **Show that the example problems are representative of the intended problems**
- **Show the method being useful in example problems**
- **Show that it is the method that is providing the usefulness alone**

When these five statements are accepted true for the method in question, it is considered evidence of the validity of that method, and thus supporting a case for a ‘leap of faith’. That is, that the method be perceived and believed to be useful, as all validation requires this confidence factor. This leap of faith can also be encouraged by validation of the method via end-user consultancy, or if possible, use in the intended problem space.

V-Square is designed for validating methods, but as stated previously section 2.2, methods and methodologies follow the same basic construction, albeit with some other qualitative logical aspects that help shape the meaning. Based on these similarities it was proposed through this work that the validation of methods and methodologies can follow the same process if those additional logical constructs are considered.

When working based on any theory, one must work from a certain school of thought from which the flow of logic in the work is carried out. When V-Square is analysed, the creators see it as a relativist tool, their perspective is that design, quality, and tacit engineering knowledge is non-finite and unquantifiable. “Best-in-class” practices can be determined by group acceptance with this line of logic. One could also argue that the structure axiom of V-Square is guided from a foundationalist viewpoint, but the point being made is that part of this verification process lies in a very subjective knowledgebase. Although V-Square has empirical components, analogies from the empirical field of medicine can be used. These analogies act as tactics for introducing more measurable, quantifiable elements into the verification and validation process. These tactics aim to improve judgements made with evaluation tools like V-Square by reducing the amount of bias, human error, and subjective judgement in the decision-making progress by replacing these aspects with numerical comparisons.

2.6.3 Lessons from medicine

Shifting qualitative aspects of the evaluation process into quantitative metrics provides a set of variables that can be measured. It also provides a tangible frame of reference when comparing one method against others, this is something industry would have great interest in. When it comes to experiment design and testing standards, few organisations are more stringent than those involved in medicine. This is due to the risk associated with the development of pharmaceuticals. (Alexander & Clarkson, 2000) There currently may be no testing standards for experiments with design methodologies, but methodologies used in medicine can be a useful equivalent. Frey and Dym (Frey & Dym, 2006) discuss in great depth how techniques in medicine are a useful analogy towards the validation of design methods. In this subsection, his work is used as inspiration in creating footholds in the validation problem.

The key component of Frey and Dym’s work was the validation of design methods, showing how analytical methods for labs must follow set standards such as U.S.FDA CGMP and ISO/IEC for their methods to be eligible for validation. These standards include parameters that can be tested that reflect the success of the product. These parameters are:

- Accuracy
- Precision
- Specificity
- Limit of detection
- Limit of quantitation
- Linearity
- Range
- Ruggedness
- Robustness

(Huber, 2010)

Note that the source document contains more parameters, but these exist mostly due to non-standard terminology across organizational bodies and can be ignored for the purposes of this paper.

Accuracy

Accuracy can be summarized as how close the test value gets to the currently accepted benchmark value. In medicine this is determined by governing bodies.

Precision

Precision, in general, is the measure of closeness between two or more samples, but is broken down into three sub-parameters. Repeatability, intermediate precision, and reproducibility, which refer to the precision over time or action (short/medium/long) and between tests or labs (same test/same lab/another lab) respectively.

Specificity

As defined in ICH, specificity is “the ability to assess unequivocally the analyte in the presence of components which may be expected to be present”. In layman’s terms, this is how effective the validation method is at analysing the one chemical component of interest and its effects even with the presence of other components that may interfere with the results of the test.

Limit of detection

The limit of detection of a procedure is its ability to detect (but not quantify) the analyte present to the lowest degree possible.

Limit of quantification

The limit of quantitation is like the limit of detection but describes the limit at which the analyte is still quantifiable.

Linearity

Linearity is the property of the test procedure that determines its effectiveness in obtaining end results that show proportionality with respect to concentration of an analyte. In short, if one testable variable can be increased or decreased, then results should show a proportional and linear effect from this change.

Range

Range is understood as the acceptable breadth of potential analyte concentration that this testing procedure is suitably apt in measuring.

Ruggedness

The ruggedness of the testing procedure is defined as its ability to produce consistent results under variable conditions. This is functionally like reproducibility.

Robustness

Robustness is the method’s tolerance to small discrepancies in the method variables, thus is a quantifier of general reliability under less-than-ideal conditions.

By setting an acceptable threshold for these quantifiable values, medical researchers can determine effective “success” of a treatment or drug and compare it to other solutions.

Design research can learn from this as many of these factors have equivalents in a design context. The specifics of such comparisons are still up for debate, but on a “closest match” standard, the relevant factors for the evaluation of design solutions can be determined, shown in Table 2-5.

Pharmaceutical Parameter	*Pharmaceutical evaluation context*	*Method evaluation context*	*Design evaluation context*
Accuracy	Proximity of the taken value to the accepted benchmark value	Ability for methodology to produce designs expected of it, embedment of requirements	End product's ability to satisfy the design requirements
Precision	Proximity in value across repeated samples	Ability for methodology to repeatedly reproduce designs that are expected of it, requirements embedded throughout methodology	Repeated satisfaction of design requirements across the project
Specificity	Ability to measure the effect of the analyte amidst the presence of other components	Projected influence that the structure of the methodology has on the end product	Attributing the effect of the methodology on the end product
Limit of detection	The lowest amount of analyte capable of being detected	Lowest amount of application from the methodology that can be considered useful	Minimal amount of methodological influence that can be detected in the product
Limit of quantification	The lower limit of analyte that is still quantifiable	Lowest amount of application from the methodology that is provably useful	Minimal amount of methodological influence that is proven to positively influence the product
Linearity	Effectiveness obtaining results that show proportional value change with respect to analyte change	Structure showing an increase in positive influence with respect to following the methodology	Product quality increased with exposure to methodology
Range	The acceptable breadth of analyte concentration measurable	The acceptable range of design situations the methodology is suitable for	The acceptable range of situations the product is suitable for
Ruggedness	Proximity in value across samples that are taken in differing labs/setups	Ability for methodology to repeatedly reproduce designs that are expected of it across variants of itself and amongst other design bodies	Repeated satisfaction of design requirements across multiple projects and different users
Robustness	Tolerance to small variances, reliability	Ability for the methodology to maintain its structure with minute changes across it	Product's reliability under non-ideal situations

Table 2-5 - Parameters from medicine imposed onto design context equivalencies

These new parameters, based off equivalents in medicine, can determine how effective or efficient the product of the method is. If these testing standards could be applied to the evaluation of methodologies, it may be beneficial. Characterisation of the empirical aspects of methodologies will aid in benchmarking and measurement. Using these parameters as measurable values in a case study will enable the evaluation of the method.

2.7 Research opportunities

At this stage in the background research, a handful of opportunities across 6 key knowledge areas emerge. These opportunities, concluded from the literature review, are laid out in Table 2-6.

Design	Novice engineers have different, specific knowledge needs when working in industry compared to their veteran counterparts.
Methodology	Recent research in best practice for methodology design has yet to be effectively utilised.
Complex systems	Complex systems engineering designs have more inherent challenges due to the nature of the projects.
Industry	Academic methods and methodologies are seldom accepted into industry due to a lack of viable proof of success, nor is the path to adoption an understood process.
Space environment	In addition to the challenges of complex systems, space systems have the additional hurdle of lacking the ability to adequately prototype or emulate the test environment.
Verification and validation	There are no formal, standard or widely accepted means of validation for design methods and methodologies, nor a guide for the creation of a methodology.

Table 2-6 - Opportunities for research from background literature

Exploring each of these subject reveals an alignment of research opportunities. The “Industry” and ”Verification and Validation” subject areas in Table 2-6 call for some investment in an empirical, standardised evaluation tool for academic models. The other challenges call for research into changes that can be made to the design process. The purpose would be to redefine, improve and optimise the design process to accommodate the identified issues.

2.7.1 The problem statements

Both sets of opportunities can be resolved via the development of a new design methodology. If the thesis solution were to take the form of a methodology, it would work towards accommodating all these aligning factors, working on the assumption that they are not contradictory. From this, the problem statement is derived:

> *"Create a verified and validated design methodology for solving complex space systems industry issues."*

Alone, this problem statement would not satisfy the needs of industry or verification and validation, thus an independent verification and validation method is proposed to be developed with the intent of guiding standard evaluation practice.

> *"Create a standard practice procedure for the verification and validation of design methods with the intent of guiding into industry adoption."*

2.8 Chapter 2 summary

The aim of this chapter was to establish potential research opportunities from six research topics.

Research into design literature showed a few ways to model and define the design process. Key findings include novice engineers' approach to design and their knowledge needs. Modelling the techniques of experts can help bridge the gap in skill between novice and experienced designers.

The concept of a methodology was explored, showing that methods and methodologies are structurally similar. The key benefit of a structured methodology is to tackle complexity and to ensure the correct procedures have been followed, enabling verification. The classifications and foundational properties of methodologies were investigated, discussing method evaluation based on parameters. There are many smaller pieces of contribution regarding the design and optimisation of methodologies, but overall, these contributions have yet to be effectively utilised.

Complexity is explored with regards to an engineering context. Interfaces between sub-functions and the transmission of information, data, energy are complexity inducers. Complexity has many forms and can be classified in many ways. The key counter to complexity is the implementation of constraints. Using design gateways give a degree of confidence to battle uncertainty in checkpoints along the design process. Establishing the early-stage requirements and problem definition are also good strategies.

The complex systems industry is an important contributor to the global economy, trading in billions each year. The effect that computer systems have had on the design process is significant with regards to complex systems and many companies now use PLM-like systems to manage their design process. Academic models are not accepted into industry as often as desired, reasons range from a lack of acceptance of usefulness, to a perceived complexity in the implementation or a lack of desire to change. The involves communication with CSE industry, finding their needs and adapting methods for them while providing useful validation data to back it up.

The space environment is a novel one, possessing characteristics that are much more hostile than earth environments. Temperature, radiation, the hard vacuum, particle charging, debris and micro-meteoroids are all tangible threats to hardware present in space. Limitations with non-destructive testing methods also cause confidence issues in the design. To accommodate this, space systems can be modelled and simulated using multi-perspective modelling.

Verification checks that the design process is being undertaken correctly and validation checks that the product satisfies all the original requirements. V-Square is a verification and validation tool for design methods. It is a step-by-step process that builds confidence in the method. V-Square proposes that once each step has been “verified”, validation is a logical inference and is implied if the process is verified. There are similarities that can be drawn between design and medicine and used to develop evaluation parameters for determining methodology effectiveness and efficiency.

Through this literature review it was determined that there were several opportunities for further research, all of which could be solved with the development of a new systems engineering methodology for space systems. This methodology could then be used as a demonstration tool for new design techniques, a standardised verification and validation tool and the eventual adoption into industry practice.

To ground this problem statement, further research was conducted to establish the details and considerations to be made in this endeavour. The next chapter discusses the in-depth research of fully defining the problem and developing solutions to counteract it.

Summary at a glance

- 6 key knowledge areas were researched to find addressable challenges with respect to space systems engineering
  1) Design – Novice engineers have certain knowledge requirements
  2) Methodology – Novel academic research is underutilised
  3) Complex systems – Emergent challenges of complex systems engineering
  4) Industry – Academic methods are infrequently adopted into industry
  5) Space environment – Testing environment is challenging
  6) Verification and Validation – Lack of standardised means of method V&V
- These issues were compiled, solution determined to be several items within one thesis
- Problem statements were generated:
  1) "Create a verified and validated design methodology for solving complex space systems industry issues."
  2) "Create a standard practice procedure for the verification and validation of design methods with the intent of guiding into industry adoption."

Next…

- Detail research defining the problem
- Recommendations on engineering methodologies
- Comparison if existing methodologies

Chapter 3

Problem definition

To form an effective response to the problem statements developed in Chapter 2, further research into defining these problems was conducted. The goal was to make changes at the engineering design methodology level to tackle issues across 6 key areas in complex systems design.

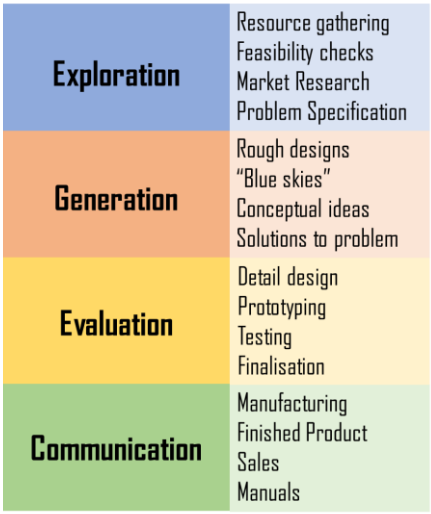
Investigation took place by looking at the positive traits of existing design of methodologies. This was accomplished through literature review of positive traits of methodologies, methodology design techniques and review of existing methodologies and the challenges facing them. Some general comparisons between methodologies are also drawn to generate some key recommendations for the creation of engineering design methodologies.

In this chapter:

- **“Designing” engineering design methodologies**
- **Recommendations from literature regarding desirable traits**
- **Comparison of existing methodologies**

3.1 “Market Research”

This chapter aligns the development of a design methodology with the PDP, showing that the design process can be followed when creating a methodology. A generic and flexible approach to design is adopted, as there is a modicum of uncertainty with regards to the details of this process. For this, Cross’ model was chosen, shown in Figure 3-1, this is because the model is simple and all-encompassing of the design process and neatly breaks it down into 4 key stages.



Exploration	Resource gathering Feasibility checks Market Research Problem Specification
Generation	Rough designs “Blue skies” Conceptual ideas Solutions to problem
Evaluation	Detail design Prototyping Testing Finalisation
Communication	Manufacturing Finished Product Sales Manuals

Figure 3-1 - Cross' Design Process Model (Cross, 2000)

The first design phase initiates market research in the relevant areas. This chapter maps the Exploration phase, where requirements and desirable traits of design methodologies are uncovered in the literature while improving the design process at the same time. The findings were then gathered, with a comprehensive list of requirements detailed at the end. These were then formulated into a set of recommendations for design methodologies.

3.1.1 Method and methodology design techniques

When designed a method or methodology, within the context of its design it can be regarded as a product (Schmidt-Kretschmer & Blessing, 2006); design methodologies have end users, designers, performance metrics, and, of course, a design process.

Methodologies as a product

The primary users of a design methodology or are engineers. In this context, the goal of the methodology is to provide the engineer with a method to achieve the design task, arrange their actions and provide support for their decisions, without biasing them. (Badke-Schaub, Daalhuizen, & Roozenburg, 2011) Methodologies are generally created by academics who research and compile the methods. In the design process, the end state is hypothesised, and the theory is tested through prototyping. The performance metrics have fewer empirical factors than physical objects, due to the theoretical nature of methodologies. Qualitative data can be turned into quantitative data, as discussed in section 2.6.3.

This chapter will be structured similarly to the chronology of the design process, treating the creation of a design methodology like the creation of a product. First, the need is identified, and existing methodologies are examined. Next, clarification of design principles and requirements takes place to develop specifications for the methodology. The final component of this chapter discusses use of literature-based techniques in the design process.

3.1.2 Identified opportunities from literature

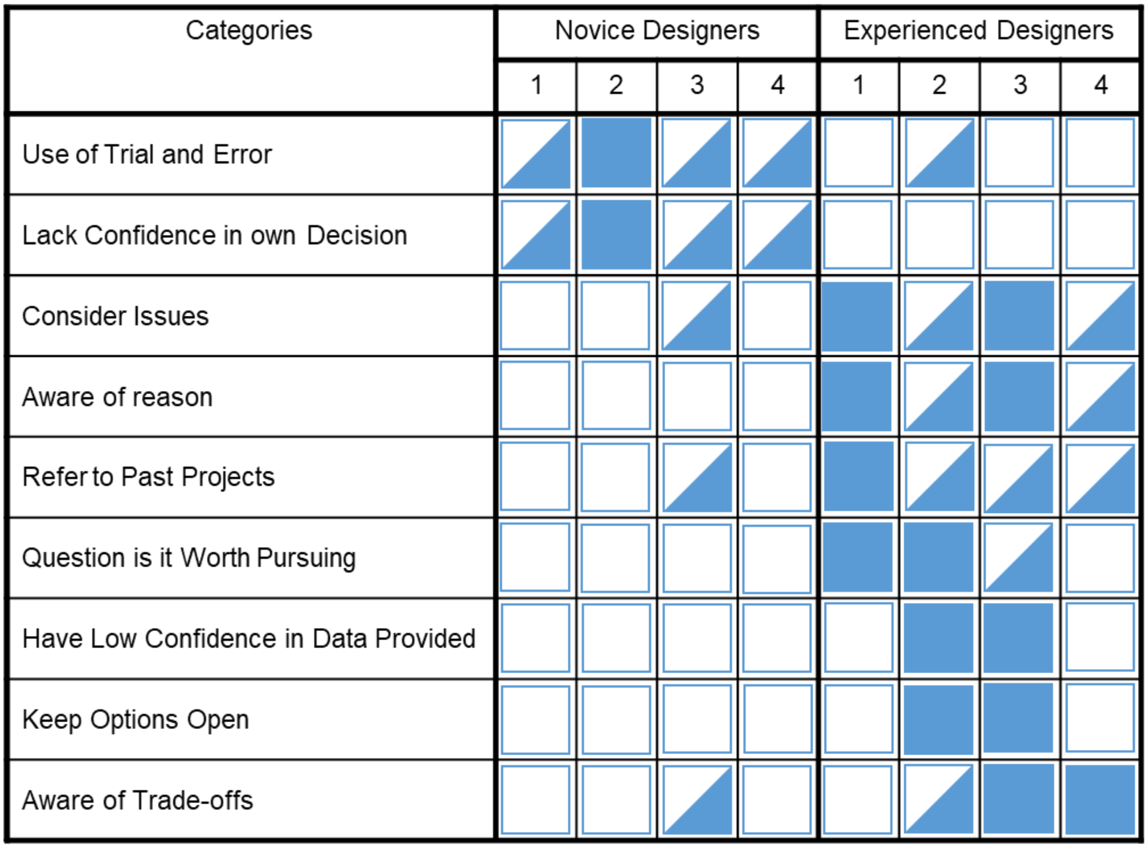
As discussed in the previous chapter, there were several challenges presented in literature that could be addressed through changes to design methodologies, summarised in Table 2-6. As such, one goal of the thesis was to design a methodology that mitigates these issues. The aim of this chapter was to provide literature foundations for design choices, such as design principles, best practice techniques and other novel ideas. These needs are used to shape the path of methodology design. Of the requirements specified in the research, opportunities will be taken to weigh the trade-off's and use the space to discuss potential solutions.

Opportunity 1 – Novice engineer knowledge needs

The first opportunity identified in the initial research was regarding the needs of the novice engineer, classified as engineers with fewer than 5 years' experience in their chosen field. To summarise the findings, it was discovered that novice engineers will know the required prerequisite information in only 35% of queries (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000). Novice engineers are often unsure of what they should be trying to figure out. They tend to take on the task one element at a time, use deductive reasoning and demonstrate poorer visualisation skills and spatial memory than their experienced counterparts. The helpfulness of a design tool is also dependant on a designer’s experience; beginners will seek out limitations to their decisions with these tools and methods. An interesting finding amongst this is that both experienced and novice designers adapt to the guidelines of a new method that they have taken on equally well.

Novice engineer traits

Typically, novice engineers are aided by their more experienced co-workers or superiors as point of consultancy. However, these novice engineers often ask questions that are ill defined, irrelevant, or just incorrect. Only 35% of their queries were providing useful information (Ahmed-Kristensen & Wallace, 2004). One proposition of action comes from the works of Ahmed, Wallace and Langdon (Ahmed-Kristensen, Wallace, & Langdon, 2001), involving the implementation of a question based problem-solving approach called C-QuARK. C-QuARK is a tool developed through findings made by Ahmed, Blessing, Wallace, and Moss (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000), where they observe the problem-solving processes used by novice and experienced engineers. Their findings indicated that novice engineers use fundamentally different approaches to the experienced engineers. Novices tended to use trial-and-error tactics and lacked confidence in their decisions while experienced engineers had a much more diverse range of strategies to drawn from, as shown in Table 3-1.



Categories	Novice Designers				Experienced Designers			
	1	2	3	4	1	2	3	4
Use of Trial and Error	◢	■	◢	◢	□	◢	□	□
Lack Confidence in own Decision	◢	■	◢	◢	□	□	□	□
Consider Issues	□	□	◢	□	■	◢	■	◢
Aware of reason	□	□	□	□	■	◢	■	◢
Refer to Past Projects	□	□	◢	□	■	◢	◢	◢
Question is it Worth Pursuing	□	□	□	□	■	■	◢	□
Have Low Confidence in Data Provided	□	□	□	□	□	■	■	□
Keep Options Open	□	□	□	□	□	■	■	□
Aware of Trade-offs	□	□	◢	□	□	◢	■	■

Table 3-1 - Occurrences of thoughts and actions (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000)

These observations were used to reconstruct the average thought process of the two groups. The generalisation of the novice pattern is represented in Figure 3-2, and the expert's in Figure 3-3. The novice engineers demonstrated they were uninformed regarding what they need to know to solve the problem and did not filter their ideas with a pre-emptive evaluation.

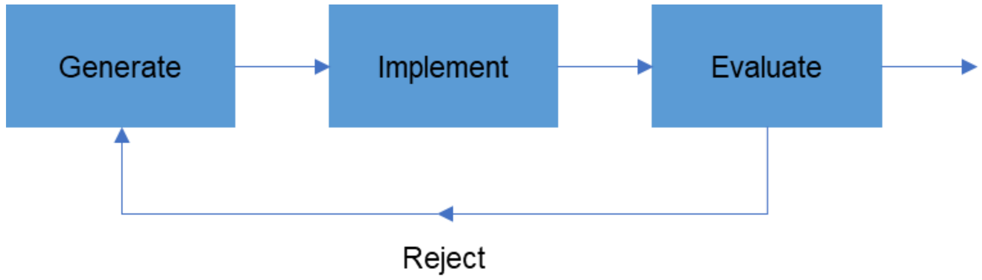


Figure 3-2 - Novice Designer's Pattern (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000)

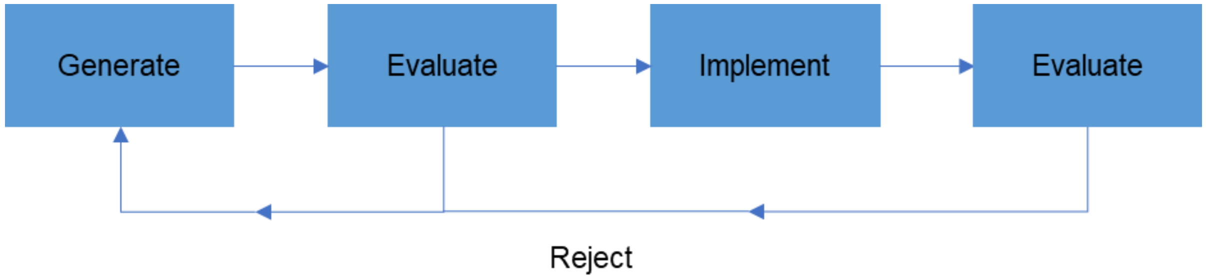


Figure 3-3 - Experienced Designer's Pattern (Ahmed-Kristensen, Wallace, Blessing, & Moss, 2000)

How C-QuARK works

The goal of C-QuARK was to replicate the successful thought processes and strategies of the experienced engineers and enable the novice engineers to engage in it using a formulated process, as shown in Figure 3-4. Novice engineers are prompted to ask themselves questions regarding the design problem to make them aware of the knowledge they need to know to complete the task.

When an engineer is faced with a design problem and they are uncertain of how to proceed, they choose one strategy from the diagram they believe is most relevant and implement that strategy. When that strategy has been exhaust, but the information is not complete, the engineer then picks yet another strategy linked to the previous one. By moving from strategy to strategy, the designer will mirror the thought processes of the experienced engineer, allowing them to determine what pieces of information they require.

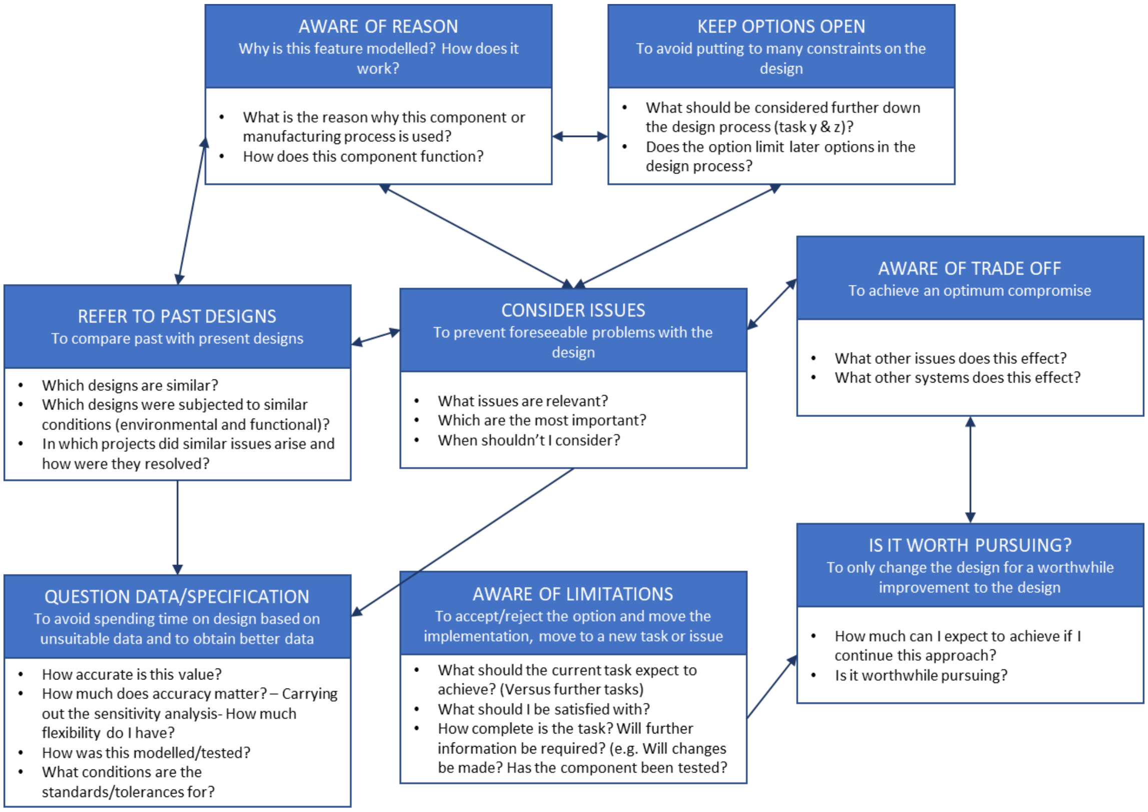


Figure 3-4 - C-QuARK (Ahmed-Kristensen, Wallace, & Langdon, 2001)

C-Quark as a procedure

From a methodological viewpoint, problem-solving schema like these can be embedded as methods and strategies at the lowest working level within a methodology, this is called the Micro-level. C-QuARK is an example of what an embedded problem-solving strategy might look like, any in-built support that guides novice engineers can be included at any level of the methodology. For example, at the Macro-scale, the highest level, the methodology is shown as a graphical representation of its aspects. By presenting the high-level information in an easily digestible format, novice engineers can glean general information regarding the methodology quickly. It is good practice to avoid intimidating the reader from learning the model, simplistic explanations and diagrams enable a streamlined learning experience to make the concept easier to communicate.

Opportunity 2 – Underutilisation of methodological research

Prevalent throughout the research literature were comments on how design research is underutilised and knowledge on methodology development is rarely taken further. Knowledge from recent research regarding properties, techniques and classifications of methodologies often goes uncited. Citations come from the basic research and findings of these papers, but the developed methods, tools and techniques are rarely implemented any further.

Reasons for lack of adoption

Reasons for research being abandoned vary by the situation. One explanation for this could be that new research may not be high quality or fully encompassing of the problem area. Speculation is also on the lack of industry interest in implementing academic models (Birkhofer, Jansch, & Kloberdanz, 2005). Transference of academic models to industry is a documented issue, as discussed in section 2.4.4 and later in this section. The lack of incentive to improve existing methods and tools leaves new research without a purpose. Another possible explanation is that the new knowledge is not useful or relevant to modern design. There are several papers that comment on methodology, method, and tool design practices. Their advice is sometimes taken on-board through the findings, but the method generated rarely carries on.

The next potentially compounding factor contributing to underutilisation of research is the heuristic culture of design itself. The nature of design is conceptual, subjective, and diffuse which is reflected on how performance of a product is measured. Performance is rooted in customer satisfaction and pure quantitative data such as speed, torque, and time only paint half of that picture. Other end user needs, such as aesthetics, “quality” and usability are subjective and cannot be easily quantified. Measuring the number of users who find a design methodology easy to use is easy, but it becomes difficult to determine ease of use.

Academic competition may also be partly to blame for low uptake in method adoption. Engineering faculties and departments in universities work to build a reputation, they do so by conducting their own state-of-the-art research, peer reviewing and publishing. In doing so the department and the authors will gain some of the prestige and credibility that goes with the work. Universities are always in competition with each other when it comes to obtaining funding, students, grants, and awards. It is then only natural to downplay an opponent’s research in favour of an in-house piece of literature. This is not to say that academia is not collaborative, researchers network globally to bring expertise groups together and publish works regularly. This is a possible explanation for a university's reason to incentivise intra-department collaboration over global collaboration.

Mitigating the issue

Alleviating this problem is more complex than demanding researchers "use more design researched methods" because it assumes that there is useful and relevant research for those researchers to adopt. Veteran academics may rest on the laurels of a work they've no interest in pursuing. Many pieces of literature remain unreviewed, outdated or with shrinking relevance to modern situations. Determining the suitability of design research for development and implementation is a viable strategy, but one that falls outside of the scope of this thesis. A viable action that was taken in the short term would be to determine if there were any relevant pieces of methodological research for this thesis. That research was used as a basis and justification for design decisions in this work, acting as an example to encourage others who are cautious of drawing on academic work.

Opportunity 3 – Lack of transfer from academic method to industry method

In the previous chapter, the existence of several types of methodologies were discussed regarding three properties: supply, demand, and application (Birkhofer, Jansch, & Kloberdanz, 2005). Academia is the primary supplier of methodologies, typically to industry demand. However, sometimes methods can be supplied regardless of demand, as they may be situational. Conversely, when a demand is not satisfied by academia, industry can devise their own methods heuristically, although potentially lacking rigor of research and testing. Of the methods that are supplied by academia to the demand of industry, there still exists a barrier to application. This transfer barrier exists for many reasons, Badke-Schaub, Daalhuizen and Roosenburg (Badke-Schaub, Daalhuizen, & Roozenburg, 2011) document these reasons as the "Deficits of design methodologies", shown in Figure 3-5.

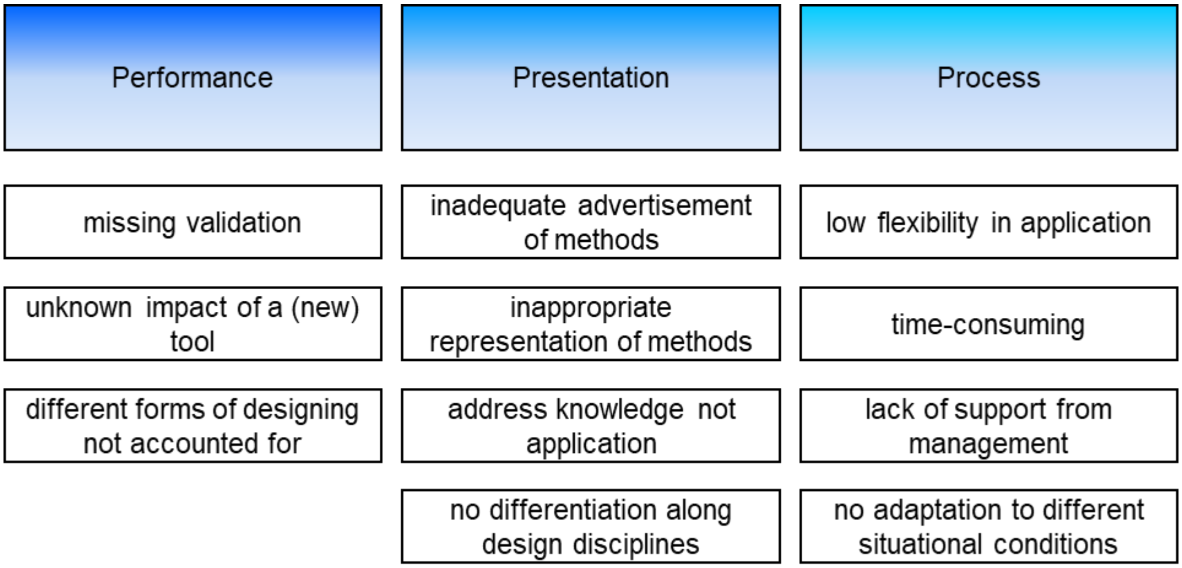


Figure 3-5 - Deficits of design methodologies (Badke-Schaub, Daalhuizen, & Roozenburg, 2011)

With some influence from Birkhofer and others, the authors conclude the main issues, categorised under Performance, Presentation and Process.

Performance

Performance issues relate to the absence of in the validity of the method. This stems from a lack of validation case studies on behalf of the creator. As identified in the previous chapter, much of the reluctance that organisations have is due to the lack of actual performance data. Typically, academic models are delivered with structural verification but lack real-world testing. As such, potential adopters have no frame of reference to draw conclusions about the method’s performance. Key comparisons and empirical validation is missing thus the impact of organisational implementation is largely unknown. This is a challenging issue to address, connections and access to industry is available through universities but direct access to a real-world, full scale example problem is limited. Industry’s perspective is that “tried-and-tested” methods are a more reliable investment than “new and potentially dangerous”. The prophecy is self-fulfilling, industry is saying “This model has no experience or refinement from industry, so we won’t adopt it into industry”. One of two things must happen to break the cycle; either a willing organisation takes a significant risk on an unknown element, or academics must do better to convince their industry peers that their methods are sound.

Presentation

The presentation of the methodology refers to effective communication of information. Referring to the supply/demand/application properties, advertising a method is one way that supply can meet demand. If industry isn't aware of the methods available to them, they will not adopt them. Typically, the discovery of new engineering tools, methods and methodologies are left to novel thinking staff within an organisation, or those in touch with the academic side. Advertisement of academic methods is not as simple as paying to show it on a billboard, it includes effective ways of communicating the benefits and Unique Selling Points (USPs). Adequate advertising avoids misinformation and represents the methods correctly. Inappropriate representation of methods leads to many downfalls of a methodology.

Mis-selling a method may lead to poor adoption strategies, organisations adopting the wrong methodology, or other negative stimuli that increase the organisations resistance to change. It is critical to consider the human element, knowledge should be accessible. The function of a method is to utilise a sample of knowledge and systemise its application into a package of work. The back door of the method is generally irrelevant and of no use to the engineer designer. Justification is important to build confidence, but too much detail can make the method difficult to learn. basic principles behind methodologies should be explained, these act as fuzzy anchors for certain behaviours. Humans can override a method but embedded within the method are the design principles that form part of the reason the method was adopted in the first place. If independent action violates these principles, then these actions do not reflect the nature of the project and will cause friction with the rest of the design process. Specifying these principles will enable individual autonomy and flexibility.

Process

Process issues often involve the intra-task efficiency of the model, for instance the trade-off of time, cost, and flexibility. Lack of flexibility in a methodology can be a hindrance to product quality. the subjective nature of design does not allow a 100% true and objective framework to exist, but by establishing boundaries with some flexibility designers do their job and make better decisions without bias. Rigid adherence to a methodology is often tiring and limiting to the designer, if there is no leeway given to the engineer, they may skip or even outright abandon the methodology.

Flexibility is also relevant to adaptability as organisations generally implement design methodologies like the product lifecycle at the organisational level. For this reason, the adaptability of a methodology to various projects and conditions is key. Adoption and application of the design methodology will require resources, this alone is sometimes reason enough to reject the methodology. The value added to the organisation via adoption of the methodology cannot be compared to the effort expended to implement it, academic validation practices rarely result in benchmarks to evaluate performance. Implementation is primarily driven by management, who make decisions, organise learning and motivate adoption. Failure to grasp the interest of the engineers results in diluted performance from the methodology, failure to grasp the interest of the management results in a no adoption whatsoever.

Opportunity 4 – Complexity and complex system inherent challenges

Challenges in adopting complex methodologies

When designing complex systems, there are inherent challenges, involving the expertise, management, process, methods, tasks and tools. In one of the author’s publications (Melville & Yan, 2016) interviews were conducted with staff at BAE systems and reports were conducted that amalgamated the key design challenges in modern ship design. These challenges, addressed in section 2.3.5, directly involve the product design process. These findings were combined and labelled “CSI challenges”. Joining the list with Badke-Schaub, Daalhuizen and Roosenburg’s list of methodology deficits a comprehensive issue matrix was created, shown in Figure 3-6. This issue matrix shows the challenges academics will face when attempting to have their methodology adopted.

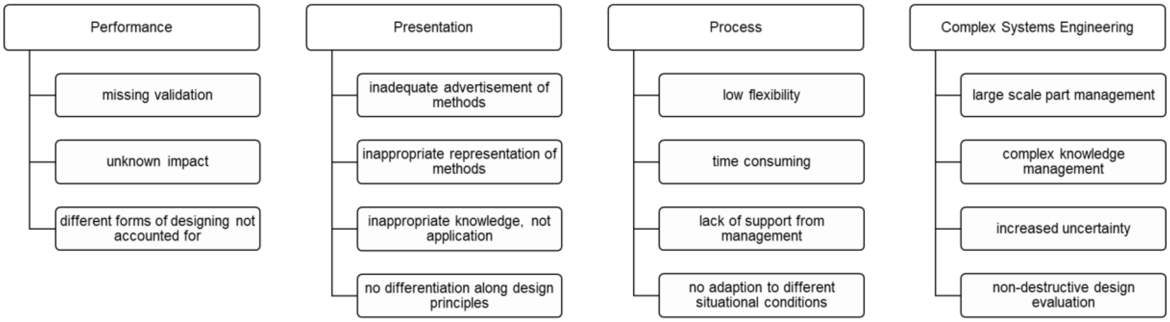


Figure 3-6 - Issue matrix for CSE methodology adoption (Melville & Yan, 2016)

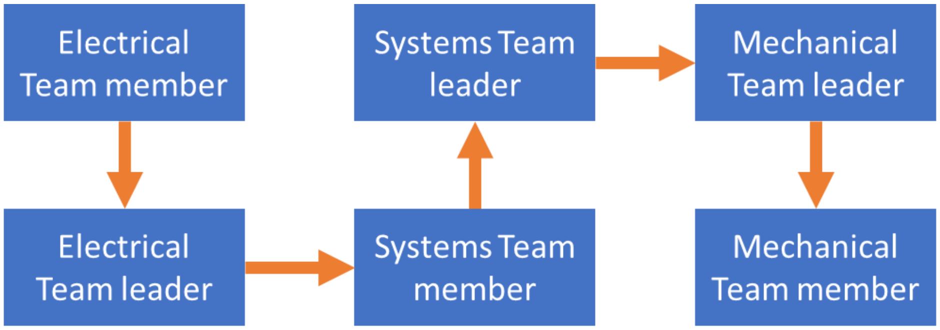
This comprehensive set of issues was intended as a basic set of requirements for CSE design methodologies where the USP is to address the issue of industry adoption.

Challenges of complexity

Complexity brings its own challenges, outlined with in section 2.3.2. Firstly, to limit the effect that deterministic chaos has on system behaviour, testing individual sub functional units should happen before assembled system testing (also applicable in computer systems). Understanding system parameters is key to allow the engineer to determine extremes of the system behaviour.

System configuration complexity should be taken seriously when developing methodology requirements. The lattice structure of relationships between elements shows that design elements interlink in a complex system, meaning changes to one piece of the design will have knock-on effects. This means that traditional “over the wall” engineering practice is a hindrance to the process. Concurrent engineering practices, which are standard in mechanical and mechatronic engineering, should be adopted by methodologies to accommodate complex relationships.

Another challenge comes from information flow across the design project. Difficulties arise when the project is complex, as multiple fields of engineering will come together with their own existing knowledge bases. Information may be passed to the wrong people, or excluded from the right people, and there is little control on its accuracy. A hypothetical scenario is shown in Figure 3-7.



Lack of knowledge regarding points of contact

Time taken to send through 5 inboxes,
information context can be lost through 5 degrees of separation

Figure 3-7 – A hypothetical information exchange within an organisation

The bigger the organisation or team, the more complicated the information network. Additionally, there is a diverse range of information: part numbers, versions, documentation, directories, sources, and so on. Knowledge management can be implemented within the methodology, in the form of computer aided tools and regulated channels that covers data, documentation and knowledge. This ensures that information is correct, uses the proper terminology, and is delivered to the right people at the right time.

The final challenging characteristic is the occurrence of combinatorial explosion, caused when a component is added that influences the system in unforeseen ways. Direct and indirect links are created between other subsystems and components, providing more links to other components. These interactions can be managed, again by computer aided tools that track intra-system links.

Opportunity 5 – Space specific considerations

In addition to the challenges in the industry context, engineering has additional challenges that arise from working in exo-planet environments.

Spacecraft failure rates

Firstly, common industry design practices involve the use of redundancy (Melville & Yan, 2016). The inclusion of redundant components and sub-systems is a direct counteraction against post launch failure rate. Tafazoli (Tafazoli, 2009) compiles data through the analysis of 156 failure instances, shown in **Error! Reference source not found.**. The author identifies that a majority of all On-orbit failures occur within three years of the launch, with over a third of failures occurring in the first year alone, shown in **Error! Reference source not found.**.

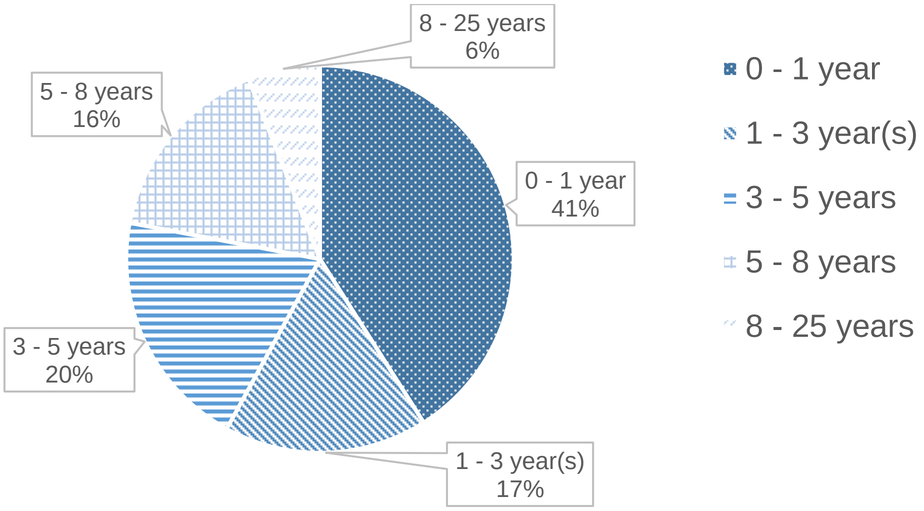


Figure 3-8 - Time of failure after launch (Tafazoli, 2009)

Of all failures, the Attitude and Orbital Control System (AOCS) is the most frequently affected subsystem, with Power systems coming in second.

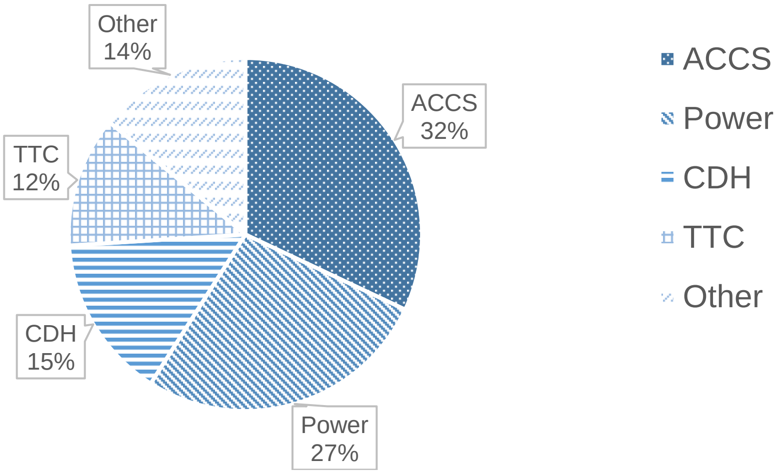


Figure 3-9 - Spacecraft subsystems affected (Tafazoli, 2009)

Electrical faults were by far the most common failure type, accounting for almost half of all failures. This was followed by Mechanical failures and software faults were the least common. It was expected that mechanical components were less reliable than electrical components, which is generally true. The data is reflective of the number of electrical components, of which there are a great many, relative to the number of mechanical components. This information is shown in **Error! Reference source not found.Error! Reference source not found.**.

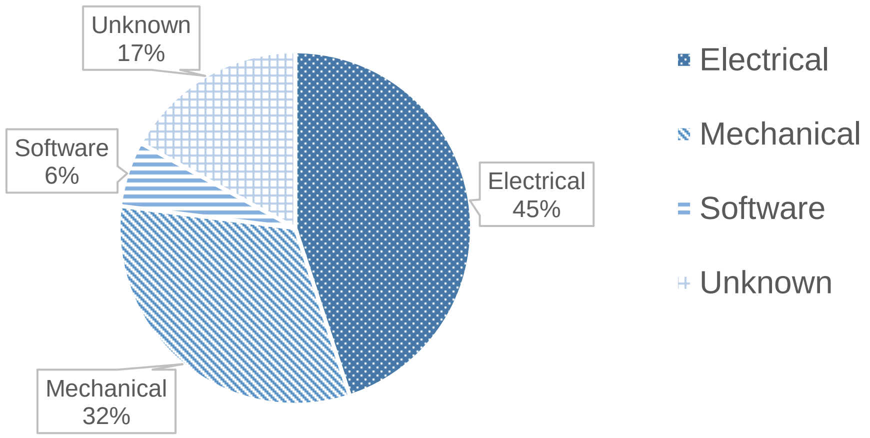


Figure 3-10 - Spacecraft Failure type (Tafazoli, 2009)

Of the failures analysed, shown in Figure 3-11 around two thirds of them degraded the mission in some way, and over a third caused mission failure.

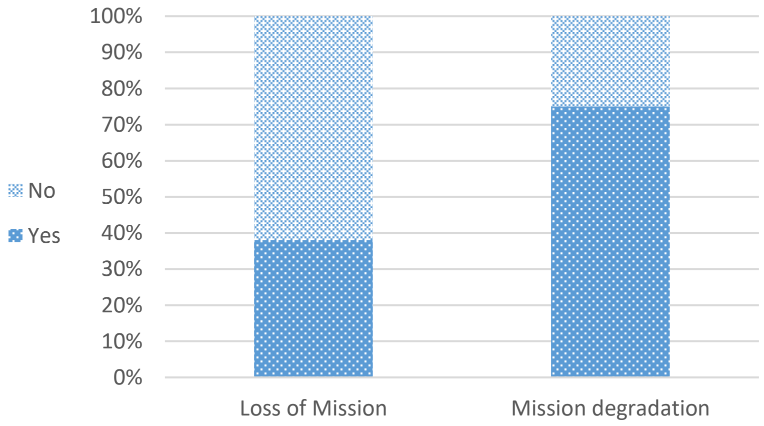


Figure 3-11 - Spacecraft failure impact on the mission (Tafazoli, 2009)

In 84% of failure cases, the problem was not caused by the hostile space environment but rather unrelated factors to this such as design or human error, shown in Figure 3-12. Tafazoli notes that the reported human error fault rate is around 8% but may be higher due to unreported operator mistakes or undocumented design flaws.

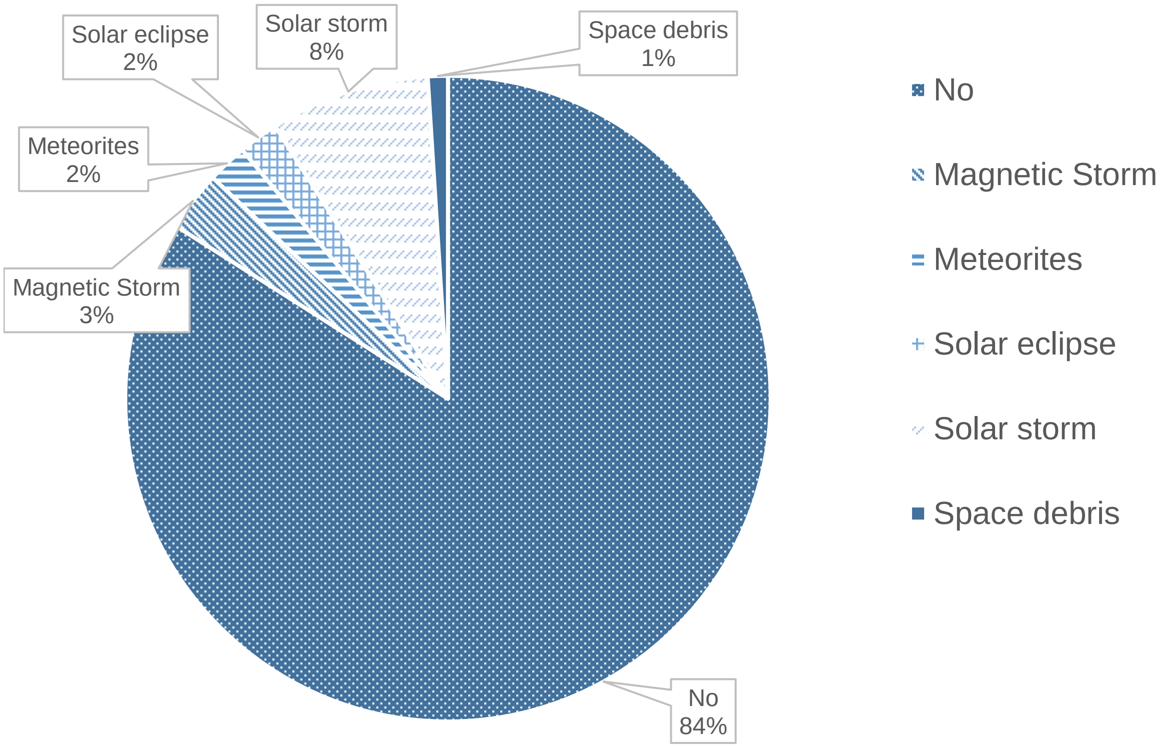


Figure 3-12 – Proportion of failure due to space environment (Tafazoli, 2009)

Finally, a breakdown of failures by component shown in Figure 3-13, with solar panels contributing to a significant number of failure instances. 40% of solar panel failures are caused by mechanical issues, mostly during deployment. The significance of this is critical as failed solar panel deployment is a cascade failure that leads potential mission failure.

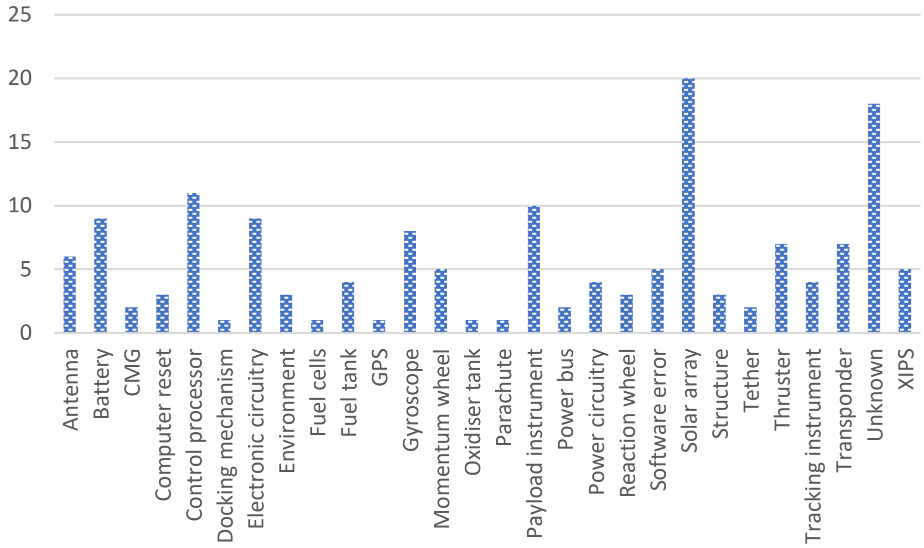


Figure 3-13 - Spacecraft component failures (Tafazoli, 2009)

Addressing spacecraft failures

Using this data, some actionable advice for alleviating these problems can be constructed. It can reasonably be suspected that design, manufacture, or assembly related issues were primary contributors to non-environmental issues. Operator errors are far easier to diagnose compared to design issues that only appear during operation. It is possible the engineers were out of the loop, and with so many elements of a design it’s hard to pin-point the root cause. To mitigate this, it is suggested that basic component and sub-system testing take place. Engineering test units of essential sub-systems should be prototyped, especially mechanical items that can be tested independently of the system in a lab environment.

The lack of full-scale prototyping opportunities poses a challenge for spacecraft and satellites. Testing of prototypes cannot be done in the target environment without heavy resource investment. The limitations on access to this environment pressures engineers to get it right first time. Normally, prototypes are created and put into test environments, however, there are two problems here.

Firstly, the cost of functional prototyping for space systems is usually high due to complexity and scale. Time, materials, and money are not at a premium when trying to build a working prototype, including onboard systems. Performing this kind of prototyping on a project will add years to the timeline and cost in the millions, if not billions. This is assuming all subsystems are in a finalised state, including software for an integrated test.

Secondly, the creation of such extreme and complex lab environments is no easy task. Industry has the technology to make near vacuum conditions, generate extreme temperatures and simulate launch vibration launch conditions. However, it has yet to advance in such a way that achieve a true vacuum or emulate threats such as ionisation. Even when this does become achievable, fabricating, and maintaining these facilities would still add huge costs to the project. As of time of writing time, these facilities are suitable to test the structural elements of the spacecraft but testing whole functional prototypes is still a costly venture.

Space environmental hazards are not as replicable as terrestrial ones, such as wind, water, atmosphere, and so on. This lack of viability directs efforts to prototyping alternatives. One potential solution is the use of computer simulation, especially multi-perspective modelling. The use of Computer Aided Simulation (CAS) has been developing steadily over the last few decades, moving from free body diagrams 3D representations. Recreating this computer-generated model allows for virtual testing in all simulated aspects such as force, vibration, kinematics, thermal load and other environmental features. In a typical CAD package, the simulation and analyses functions are partitioned, meaning only one type of simulation can be done at a time. Multi-perspective modelling is the amalgamation of these individual perspective models into one comprehensive analysis. The benefit of performing this is to gain insight into the compounding effects of multiple influences at any one time, which results in higher accuracy for a robust design.

Opportunity 6 – Lack of validation and verification standards for design methodologies

Validation and verification are essential parts of the design process, products undergo evaluation at various stages of the design depending on the methodology used. As discussed in section 3.1.1 design methodologies can be treated as products; they have users, requirements and are “designed”. Academics will try to verify and/or validate their methods, either by association against the initial requirements or by providing theoretical grounding for their decisions. In very few cases are academic tools used to validate these methods, but rather generic logical reasoning. Industry quoted the lack of validation as a contributor to lack of adoption; thus, some action must be taken to solve this. It could be argued that industry could take short term risks to trial academic methods, but academia also must understand that this is a hard sell. It is outside the scope of the paper to speculate how the industry can respond to these issues; this thesis pursues a route in which academia acts to mitigate the problem.

New design method validation standards

A universally beneficial approach would be to develop verification and validation standards for engineering design methods. This will involve drawing from a pool of existing and accepted means of validation, utilising state-of-the-art developments and satisfying academic knowledge development. This will satisfy industry’s desire to consider new effective alternatives, being familiar with a set of standards used to evaluate methods enables them to compare existing methods. Hypothetically, it will also increase the overall quality of methods that come from academic circles. Academics would follow the standards, competing with other methods that also adhere to them to be utilised by industry. This is only possible if the standards themselves are meaningful, useful, and worth applying. To meet this requirement, the means of validation should also be validated to provide a replicable series of studies that are comparable.

3.1.3 Modern day challenges for methodologies

Methodological design practices have changed many times since their inception due of historical and modern developments. These changes were mostly driven by technological advancements in the past few decades alone. Methods that were developed before or at the beginning of the computer age need revision to update and contextualise themselves with the modern engineering environment. (Binz, Keller, Kratzer, Messerle, & Roth, 2011)

Information and Knowledge management

Globalisation of the design lifecycle requires new information handling methods, both inside an organisation and between organisations. This is usually to bring in specialists from another department or country, reduce costs through personnel or manufacturing facilities, or to combine resources improve effectiveness and efficiency. Collaborative design of this nature has many issues.

Remote working

Firstly, the teams work remotely from each other, they are out of reach and it’s difficult to build rapport with them. Utilizing the skills of these people becomes difficult, it is hard to work at full effectiveness and mistakes get lost in translation. Usually, these collaborative efforts are within an organisation, or are from passing information to manufacturers, with which there is moderate exchange. Even so, the data problem exists, embodied in outsourced manufacturing. Take for example 50 years ago, if a foreign body required manufacturing drawings, they would have to be copied, bound, and mailed, taking days or weeks. If there were issues discovered on inspection, the manufacturers had no immediate way to give feedback outside of a call or mail. This problem is iterating, with no upper limit on feedback iterations. Ultimately this can push back deadlines and affect project costs.

The modern solution to these information problems can be computer based, specifically the use of information management tools, databases, and networks. Product Lifecycle Management (PLM) systems allow computers to be networked to a central database where all documentation and data is available. The PLM system interfaces with this data and can act as a communicative tool for project management. Other functions, such as timeline management, document submission control, change tracking and task assignment, also assist the design process. This interface any of the project staff to understand what they need to do and when, while keeping up to date with relevant project material. Project managers assign duties and keep track of resources. This facilitates the knowledge and management aspects of people-heavy projects and reduces effort on information driven tasks.

IT tool implementation

The use of computers in a network can help mitigate and simplify many of the challenges facing distributed design teams. This includes high-level use of computer systems for project management, but modern innovation has produced software to aid in specific tasks. Continuous improvement is a company driven goal and coupled with an engineering environment that deals with sophisticated products, the need to better design techniques becomes apparent.

Computers have the capacity to run software tools, or accommodate method methods digitally, allowing engineers to utilise a virtual environment to help optimise their design tasks. One well known example of this is Computer Aided Design (CAD). CAD programs allow engineers to create virtual representations of components or systems. Once the engineers have this, they can generate manufacturing drawings or assign properties to the model to perform simulations. Loads, gravity, fluid dynamics and thermal properties can all be simulated, removing the reliance on physical prototypes and testing, along with the associated resource costs. Physical testing and prototyping are still recommended where possible, but the CAD simulation removes redundant iterations.

CAD, while providing the solution to complex design requirements, also brings challenges of its own. Using CAD requires specific knowledge and training, and the use of parametric design must be considered with complex systems. Changes in the interfacing between sub-systems may inflict form changes in the model. For this reason, parametric values are used to base the dimensions on other variables or reference points. Using this technique, radical changes that have knock on will not be so problematic, as the model will be re-adjusted automatically.

Specialist products

Standardisation is generally a boon for engineers, it ensures component availability and provides constraints. Standardisation can only go so far in conventional product development due to developing engineering demands. Delivering Design-to-Order (DTO) products may involve forgoing standard parts or procedures. This is no truer anywhere else than in the realm of complex system design; no two designs are alike. Starting a new system design based on learnings from the previous contract may involve top-down design from scratch. Very few elements come as standard and human errors, deviations from the process, and backtracking will occur. Standardisation that is independent of a global market can often create situations where there are redundant or stop-gap or localised standards. Foreign markets may not abide by these and thus cannot contribute to the benefits of standardisation.

Standardising solutions

Potential solutions to this problem involve mixing international markets and adoption of a specific scope of industry standards. This scenario has happened with electronic components, and standards such as ISO, DEF and MIL STD are commonplace. However, for it to happen on a methodological basis is somewhat unlikely. It assumes that a company would throw away their internal market advantage to divulge the secrets behind their efficient or effective operation. Secondly, the range of complex systems that can be designed is too great to standardise a single approach, unless that approach considers flexible product creation. One can achieve this by standardising parts of their process. There are a vast number of organisations that make a whole range of products like ships and spacecraft to cars and robotic systems. These variables can be represented by flexibility and compatibility a standard element of a design methodology, i.e. make a methodology that can be used in all or most of these fields. This is not a direct solution to ever-increasing product diversity, but rather a means of keeping the design process of those products in a robust yet flexible state capable of handling future demands.

Overall, modern-day innovations allow engineers to go further than pencil and paper ever could, providing the capability to design complex products effectively and efficiently. Although these modern fixtures require design organisations and engineers to meet specific requirements, the benefit of utilising modern technology increases project efficiency (time and cost) and increases product efficiency (robustness and capability). The standardisation of design methodology elements plays a part in reducing project complexity.

3.2 Specifications from literature

3.2.1 Desirable properties of design methodologies

Literature on the properties of design methodologies is uncommon, but there a few core works cover the concept thoroughly. Keller and Binz (Keller & Binz, 2009), researched the aspects of engineering design methodologies, summarised in Table 3-2. The framework covers a list of requirements that benefit design methodologies, grouped into similar topics. The requirement groups in the second column of the table represent aspects of the design methodology as a generalised component.

A	Revisability	Validation Verification
B	Practical Relevance and Competitiveness	Innovativeness Competitiveness
C	Scientific Soundness	Objectivity Reliability Validity
D	Comprehensibility	Comprehensibility Repeatability Learnability Applicability
E	Usefulness	Efficiency Effectivity
F	Problem Specificity	Problem Specificity
G	Structure and Compatibility	Handling Complexity Problem Solving Cycle Structuring Compatibility
H	Flexibility	Flexibility

Table 3-2 - Requirements on Engineering Design Methodologies (Keller & Binz, 2009)

This revised list with group explanations was presented in another, revised work (Binz, Keller, Kratzer, Messerle, & Roth, 2011) and is shown in Table 3-3.

Aspect	Group Description	Grouped Requirements
Normativity	*Revisability* by appropriate and accepted means	Validation
		Verification
	Scientific soundness by backing up the hypotheses of a methodology	Objectivity
		Reliability
		Validity
Didactics	*Comprehensibility*	Comprehensibility
		Repeatability
		Learnability
		Applicability
Uncertainty	Providing a *structure* for complex tasks and problems and *compatibility* with different environments	Handling complexity
		Problem solving cycle
		Structuring
		Compatibility
	Providing *flexibility* for the designer using degrees of freedom when applying a methodology	Flexibility
Competitiveness	Practical relevance and *Competitiveness* by satisfying a need for a methodology	Innovativeness
		Competitiveness
	Usefulness	Effectivity
		Efficiency
Match and Limit	*Problem Specificity* allowing links between an assignment and a matching methodology, and defining the application limits of a methodology	Problem Specificity

Table 3-3 - Engineering Design Methodology aspects (Binz, Keller, Kratzer, Messerle, & Roth, 2011)

The requirements are based on literature research done by Binz and Keller, the justification for determining these requirements is representative of design engineering philosophy. As stated, before a design methodology is a product, and to design it the requirements must be known. Requirements provide a guide for design and a means of evaluating it. The research is especially relevant as their focus was on mechatronic papers. This framework was already being used at the Institute for Construction Technology and Technical Design (IKTD) in Stutgart for "assessing, choosing and developing engineering design methodologies and support".

To understand how to use it as a tool the requirements must be defined specifically. This thesis proposes that, through compilation of research on design methods and methodologies, a conclusion can be drawn regarding the requirements of design methodologies. Below, these requirement sets are defined for context.

Revisability

The requirements for this group contain verification and validation of the design. While the framework does not recommend a means of validation, the work acknowledges the need for a formalised verification and validation procedure to accommodate "diffuse objectives and diffuse objects". The "Verification" requirement checks that the methodology "do the right things", and that the "Validation" to "do things right". The arbitrary nature of this type of definition prompts the authors to echo Bailey et al's (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000) views on scientific knowledge being a "socially justifiable belief".

Practical relevance and competitiveness

These requirements are important to industry application besides the methodology's usefulness. "Innovativeness" describes the novel aspect of the methodology, its USP or specialisation. This can take many forms, some methodologies have a wide range of uses, accommodate a specific method, or tool, or focus a specific part of the design process, such as in Design for X (DfX). "Competitiveness" is the methodology's ability to remain viable when compared to other methodologies

Scientific soundness

Approaching the design of a methodology from an objective viewpoint helps eliminate a lot of subjective and human errors. It also checks the methodology against state-of-the-art and best practice. (Hubka & Eder, 1999) The design process is never truly objective, but the creation of a systematic design process has its roots in objectivity as a firm basis for its assumptions. Ensuring that the methodology originates from robust scientific origins helps verify the methodology and ensures that the product and design process is sound. To be "Objective" in this regard is to be consistent, and to be consistent is to be reliable, reliability here refers to the analysis of the methodology. This is also a fundamental step towards proving validity and avoiding solution bias, which can be done by ensuring the methodology is independent of the solution. Overall, validity is achieved when the methodology's objectives reflect what it can achieve.

Comprehensibility

To be "comprehensible" the methodology must be justifiable provide reasoning for each action within it. The literature refers to two views, a priori and posteriori, otherwise known as before and after. The methodology should first explain when, how and why things must be done, and enable the end users to provide the same reasoning after the fact. Hindsight is a human tool to evaluate previous decisions, if no discernible advantage is witnessed after an action is carried out then it cannot be justified. Foresight is much rarer, the ability to predict the effect an action will have on the product or process helps make correct decisions. To be "comprehensible" is to bake these tools into the methodology so that users can understand the logic behind decisions and make them usable. The descriptive element requires task descriptions, not just justifications. Having these aids repeatability, ensuring adherence to the methodology and aiding in comparative tasks. "Learnability" is key, as the learnability of a methodology is proportional to its performance, acceptance, and usage. "Learnability" is teachability, and to aid this the methodology can follow some common principles, such as using standardised language, logical and intuitive tasks, and graphical representations. The principles should draw from the designer and the methodology's, common knowledge base. This also measures the willingness of users to pass on the teachings, which is often self-driven (Schmidt-Kretschmer & Blessing, 2006) as the desire to use and communicate the methodology is promoted by positive reinforcement. Rewarding progress through milestones or achieving a visible and useful outcome reinforces these positive feelings. “Applicability” is viewed both from a design and organisation perspective, the model must accommodate being both taught and used within an organisation.

Usefulness

“Usefulness” of a methodology is measured from two performance factors: effectivity and efficiency. “Effectivity” is a measure of the methodology’s effectiveness, how close result was to the target, or how satisfied the customer was. This measurement requires knowledge on what the desired end state was and the actual state. The smaller the difference between the two, the more effective the methodology was. “Effectivity” also has a subjective component called perceived effectiveness. A methodology can be considered effective based on the majority perception by its users (Ehrlenspiel, 2003). While this not objective, the subjective performance elements such as ease of use and learnability cannot be quantified so easily. The objective elements meet the subjective when the rate these concepts are understood can be determined by seeing how many found it “easy to use”. The comparisons of opinions can be made into a metric. “Efficiency” is a measure of effort expended to achieve the product. This can be extended to the methodology’s ability to accurately predict resource use over the course of a project. This also includes the efficiency of implementation of the methodology into the organisation.

Problem Specificity

Enabling the user to determine whether the methodology is applicable is a sign of a methodology with good “Problem specificity”. The methodology should ensure that the user has information regarding its scope, such as what fields of design, industries, or complexities are suitable.

Structure and Compatibility

Complexity can be approached and handled in various ways in the design process, one method is to transpose problems into tasks. Structuring the design problem to simplify decision making helps the engineer, as long as the designer is not biased, and the decisions are mapped correctly. Oversimplification is an issue, as the context may change through translation. If the solution derived from the task is suitable to the original problem, then the translation was effective. Strategies for structuring involve the subdivision of objectives and tasks or suggesting design methods. This is also a consideration for the problem-solving cycle, sometimes a problem-solving schema is presented as part of the method. “Compatibility” also needs to be explored through interactions with the methodology. These interactions involve tools, organisational and project structure, methods, engineering disciplines and knowledge management. Compatibility should remove the barriers that might be present in adoption, but only if the methodology is suitable.

Flexibility

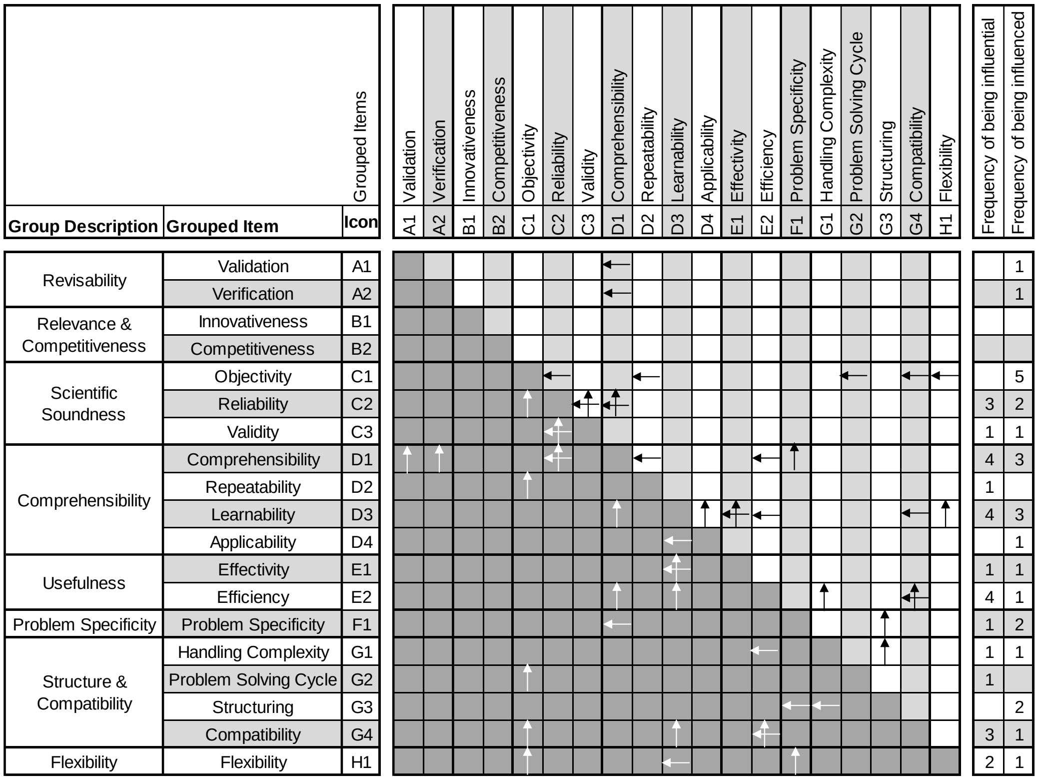
Enabling autonomy of the engineers or actors in the design process allows a methodology to be flexible. This flexibility may allow selection of methods for a problem, so long as it serves to improve the process. Allowing “wiggle room” to human judgement will allow some freedom to accommodate unforeseen circumstances like dynamic specifications, budgeting issues, other human errors, or other process failings. A good methodology will account for this natural behaviour, it may provide the intended procedure while maintaining room for deviation by providing viable alternatives. Organisational culture is a behavioural phenomenon that must be accommodated within flexibility.

The literature authors proposed these aspects of design methodology and consider them as requirements, thus if a methodology is to be well designed it should satisfy each of these requirements. The degree with which these requirements are met is a representation of how effective or efficient the methodology is. Many of these aspects are also comparable to some degree, allowing methodologies to be benchmarked. If one can quantify a tried and tested design methodology efficiency or effectiveness in this context, it may also be done for developing models, allowing them to be compared on a theoretical level. A shorthand description of each of the methodology requirements is shown in Table 3-4.

REQUIREMENT	DESCRIPTION
VALIDATION	Doing things right, ensuring that the methodology produces a product that satisfies the end user requirements
VERIFICATION	Doing the right things, ensuring that the methodology follows the design process
OBJECTIVITY	Proving the methodology has a firm basis in objective findings and accepted design research
RELIABILITY	A robustness in delivering similar results if a similar set of parameters is used
VALIDITY	The ability for the methodology to achieve the goal of producing a product that satisfies
COMPREHENSIBILITY	To provide reason and justification for planned action or decision, and to allow documentation to be performed post-action
REPEATABILITY	The ease of adherence to the methodology across multiple usage scenarios, and the effectiveness of results comparison
LEARNABILITY	The ease of learning of the methodology knowledgebase, the intuitiveness of the processes and the effectiveness of passing itself on through teaching
APPLICABILITY	Suitability of a methodology to be adopted by an organisation and for adoption to a type of problem, ability to overcome resistance to change
HANDLING COMPLEXITY	Systemising of complex problems into tasks, contextualising that task using the initial problem's objectives
PROBLEM SOLVING CYCLE	A method or tool that supports the problem-solving process by providing strategies or routes to pursue
STRUCTURING	Simplification or subdivision of tasks into subtasks or component problems that can be handled one step at a time
COMPATIBILITY	Intra and Inter-Methodology interactions, how the interactions between methods, tools and the design process meld with organisational culture
FLEXIBILITY	Degree of freedom in application to the specified problem, allowing for the overruling of method choices, use of human judgement, accommodation of adjustment for unforeseen circumstances
INNOVATIVENESS	Some novel aspect(s) of the methodology that present a satisfactory reason for using it, it's USP, or its forte
COMPETITIVENESS	The viability of using the methodology relative to existing choices in terms of performance
EFFECTIVITY	Effectiveness when measuring the desired state of the product with the actual state, perceived effectiveness in use
EFFICIENCY	Effort expenditure to achieve the result and implement the methodology into the organisation, material (time, money, material, etc) efficiency
PROBLEM SPECIFICITY	Explicit determination of applicable problem types, engineering fields and industries that benefit from the use of the methodology

Table 3-4 – Methodology requirements summary

These requirements will influence each other, and thus the designer must consider how prioritisations of these properties will affect the methodology. The literature author maps out these specificities in Table 3-5. Comprehensibility, Learnability and Efficiency are large influencers on the rest of the properties based on the “frequency of influence”, shown in the right-hand column. These requirements should be treated as key element when designing a methodology. Objectivity is heavily influenced by other properties and thus should be monitored closely during the design process. Using this representation, methodology creators can determine which properties are dependants. This is useful if the designer wishes to maximise the viability of these properties. Iterative and concurrent design may balance the relationships between these elements in the design process. This kind of representation forms the baseline of considerations to be made when implementing the desirable properties outlined in this section.



		Grouped Items	Validation	Verification	Innovativeness	Competitiveness	Objectivity	Reliability	Validity	Comprehensibility	Repeatability	Learnability	Applicability	Effectivity	Efficiency	Problem Specificity	Handling Complexity	Problem Solving Cycle	Structuring	Compatibility	Flexibility	Frequency of being influential	Frequency of being influenced
Group Description	**Grouped Item**	**Icon**	A1	A2	B1	B2	C1	C2	C3	D1	D2	D3	D4	E1	E2	F1	G1	G2	G3	G4	H1		
Revisability	Validation	A1								←													1
	Verification	A2								←													1
Relevance & Competitiveness	Innovativeness	B1																					
	Competitiveness	B2																					
Scientific Soundness	Objectivity	C1						←			←							←		←	←		5
	Reliability	C2					↑		←↑	←↑												3	2
	Validity	C3						←↑														1	1
Comprehensibility	Comprehensibility	D1	↑	↑				←↑			←				←	↑						4	3
	Repeatability	D2					↑															1	
	Learnability	D3								↑			↑	←↑	←					←	↑	4	3
	Applicability	D4										←											1
Usefulness	Effectivity	E1										←↑										1	1
	Efficiency	E2								↑		↑					↑			←↑		4	1
Problem Specificity	Problem Specificity	F1								←									↑			1	2
Structure & Compatibility	Handling Complexity	G1													←				↑			1	1
	Problem Solving Cycle	G2					↑															1	
	Structuring	G3														←	←						2
	Compatibility	G4					↑					↑			←↑							3	1
Flexibility	Flexibility	H1					↑					←				↑						2	1

Table 3-5 - Design Methodology requirement influences

In short, these requirements pave the road to producing higher quality methodologies. Monitoring the interactions or trade-offs between these requirements will help achieve an effective solution.

3.2.2 Principles of methodology design

The gap between academic development and industrial application of design methods is a common topic explored in this section. To address this concern, Birkhofer and Kloberdanz (Birkhofer, Jansch, & Kloberdanz, 2005) formulated 10 principles for designing or transitioning design methodologies into industry dubbed the “Ten Commandments of successful transfer”.

The commandments were composed of advice from the authors regarding their experience and research on improving success of methods being used in practical applications.

Commandment 1: Design is not design – Meet the Design Situation!

The first commandment says that there should be consideration towards the design situation, and that design includes more than just the tasks. Other aspects such as resource management, procedures and concurrency of engineering disciplines must be considered. Design research can work to transfer design rules into processes and tasks that can be performed in industry, thus systemising and simplifying the process.

Commandment 2: The times have changed – Deal with current design tasks!

It is important to recognise that design practices have changed drastically in the past 50 years due to cultural, knowledge and technological change. To the modern academic, designing methods with consideration to things such as globalisation, the internet and CAD might seem normal. However, for the transference of old methods into new applications this point must be reiterated.

Commandment 3: Focus on methods for best processes, too!

The third commandment demands that the task planning and management is considered in design. Methods that deal with the planning of tasks, allocation of resources, and development of a product strategy are appealing to industry and possibly underrepresented in current solutions.

Commandment 4: Don’t forget organization!

As explored by Keller and Binz’ (Keller & Binz, 2009) work, the inclusion of organisational aspects in compatibility is important to the adoption process. Paying mind to company cultures when designing the method could help make it widely compatible. The method should adhere to common understandings of design concepts throughout organisations.

Commandment 5: Methods have to have a processable result

Methods being put forward into industry must be systematic to allow their chronology to be documented. The user should be able to produce documentation, or graphical representation, on the process and the outcome for analysis. This is important for justification, deliberation, and concise distribution of information to other parties involved in the design process. This ties in with Binz and Keller’s needs for a priori and posterori views.

Commandment 6: Users use methods – Meet the designers!

Consideration should be given to the people who design, not just the users but also the initiators and the implementers. Upper management are initiators, driving the need for organisational change and demanding state-of-the-art methods. Middle management will implement and integrate the methods into their project and processes, where they are learned and used by the design team. Each of these roles look for something different within the methodology. Upper management look at novelties, raw efficiency or effectiveness, middle management will consider the effort it will take to implement this method into their plans, designers will look for ease of use. Consider communication of these results between parties, transparency aids acceptance

Commandment 7: Teach theory - But train methods!

Methods are rarely fully taught through lectures or one-way learning experiences; self-reflection and usage is much more effective at reinforcing methodology concepts. Novice designers will naturally adapt to method guidelines without intimate knowledge of them.

Commandment 8: Design is difficult enough – Keep design methods simple

Simplicity comes from several factors, such as availability, effort, learnability, and support. A simple method is a desirable method.

Commandment 9: The need for software-tools

CAD is commonplace amongst design, and computer aided tools are also important considerations for methods. The benefits of software include formatting, access to support and the automatic generation of post-process data. Consider how engineers work with these tools.

Commandment 10: Motto: Get on with design methods and talk about experiences

The final commandment declares that the creator of the method gets involved with industry. This encompasses advertisement and demonstration of the benefits of the method and listening to feedback regarding improvements.

Pahl and Beitz’ requirements

Pahl and Beitz (Pahl & Beitz, 1996) also weigh in on their "musts" for design methodologies. According to them, a design methodology must:

- Allow a problem-directed approach, i.e., it must be applicable to every type of design activity, no matter which specialist field it involves
- Foster inventiveness and understanding, i.e., facilitate the search for optimum solutions
- Be compatible with the concepts, methods, and findings of their disciplines
- Not rely on finding solutions by chance
- Facilitate the application of known solutions to related tasks
- Be compatible with electronic data processing
- Be easily taught and learned
- Reflect the findings of cognitive psychology and modern management science, i.e., reduce workload, save time, prevent human error, and help maintain active interest
- Ease the planning and management of teamwork in an integrated and interdisciplinary product development process
- Provide guidance for leaders of product development teams

Many of these needs align with previous literature, which is good news regarding scientific consensus. These suggestions must be considered by future methodology developers as advice from experts, which should lead to greater research quality. In Chapter 4 the paper will work on combining these literature findings and suggestions into a comprehensive list of requirements and desirable properties. These will then be used to generate specifications for an example methodology and apply them.

3.3 Comparing design methodologies

To grasp what makes a methodology strong or weak in each of its aspects, a comparative review of key existing methodologies was carried out. In this section, some relevant methodologies are studied to identify common positive traits to carry forward to design.

3.3.1 Pugh's Total Design

Overview and Structure

Pugh's Total Design Model (TDM) is a quintessential product design methodology and is well known in academic and industrial circles. Pugh (Pugh, 1990) identifies Total Design as "the systematic activity necessary, from the identification of the market/user need to the selling of the successful product to satisfy that need." It has a sequential view of design engineering that spans product trigger to sales and is very traditional in its process. This is represented by the "Design core", shown in Figure 3-14. The design core represents the stages within the design process.

- Market
- Specification
- Concept Design
- Detail Design
- Manufacture
- Sell

The boundaries shown projecting from the specification core represent the Product Design Specification (PDS) boundary, which constrains the design from that point forward. The lettering is representative of the PDS elements, changing in order of importance to the project based on the stage, specified in Figure 3-14. Pugh does this to show the constraints that the PDS imposes on the design to simplify the process. The final two elements of the model are the technology/technique inputs and design influences. Pugh recognised that this was an evolving concept and thus relied on technologically independent techniques.

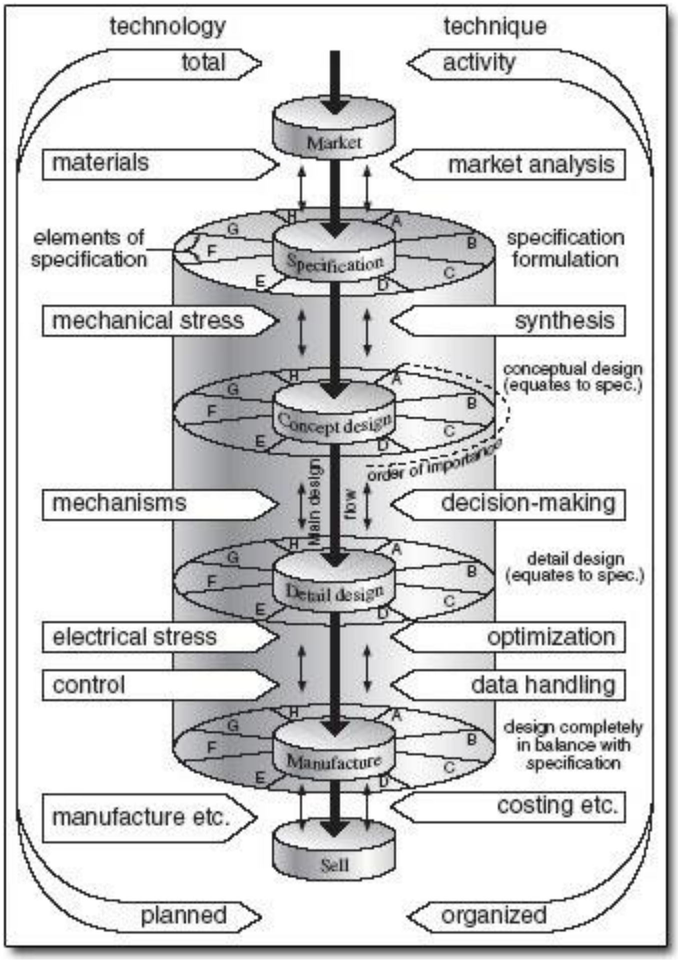


Figure 3-14 - Pugh's Total Design Model (Pugh, 1990)

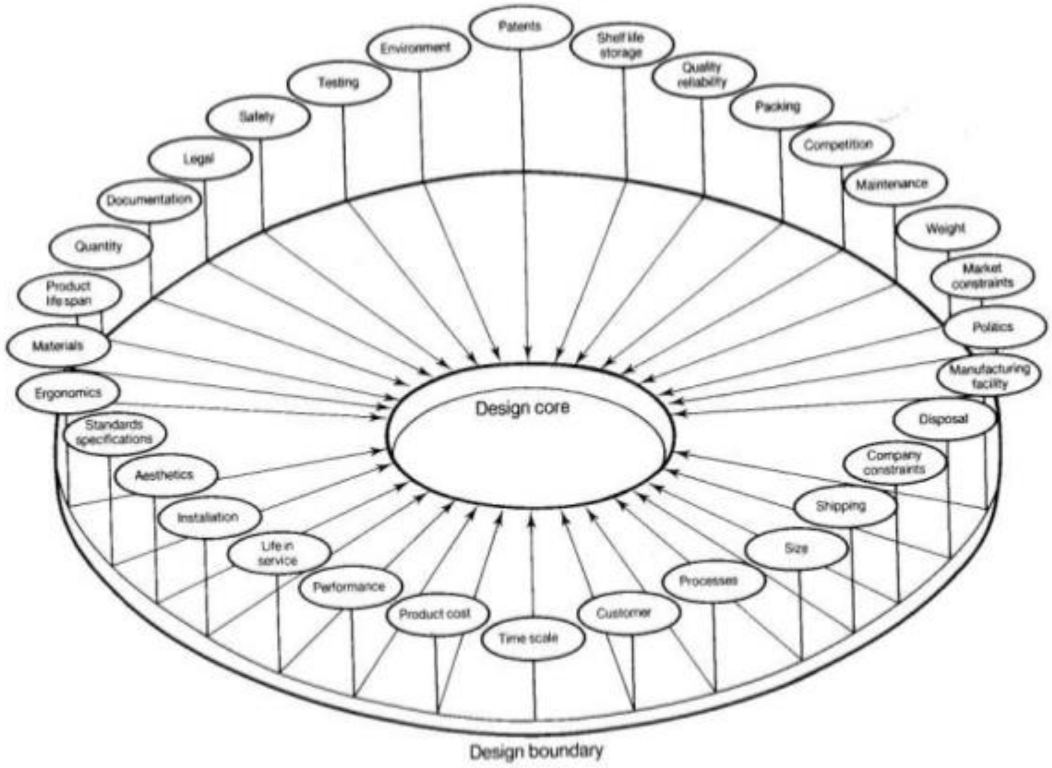


Figure 3-15 - Pugh's PDS elements (Pugh, 1990)

USPs

Pugh's model considers the entire product side of the design process, from need to marketing. This is unique to design process methodologies, which tend to end at design hand-off or manufacturing. The PDS element structure is also a useful component of the methodology, key headings are shown in the visual representation and designers can categorise and organise specifications based on these headings. This is an intuitive mapping of the design specification process that is useful for beginners. The usefulness of the model is also reflected in is flexibility, as it can be applied to any kind of commercial product providing that it is not overly complex.

Theoretical validity and use

TDM is well used in industry and is a common model a university level, especially at the University of Strathclyde. It is representative of the industry level of design process for commercial products, the limitation of the model is its inability to accommodate design of more complex or large-scale systems. While it has iterative steps, it does not explicitly support concurrent engineering practices, nor does it contain evaluative steps such as milestone reviews. Regardless the methodology is very robust, it has been tried and tested in industry and is well accepted. Its theoretical standing is solidified by its use of verified design methods, which makes the methodology heuristically valid. From a methodology design perspective, one of the most interesting features of the methodology is the literature behind it. Total Design is a book that contains an overview of design and engineering concepts and practices, it teaches the methods, background and use cases. It is an educational tool and manual rolled into one book.

3.3.2 Waterfall/V-Model

Overview and Structure

The V-model originated as a design methodology for software development and is a sophisticated refinement of the waterfall model. The basic format of the model is a sequential, staged design process that is organised in the shape of a V. This structuring is important as it demonstrates one of the core features of the model, shown in Figure 3-16. The model originated in software design but has been extended to product and system design.

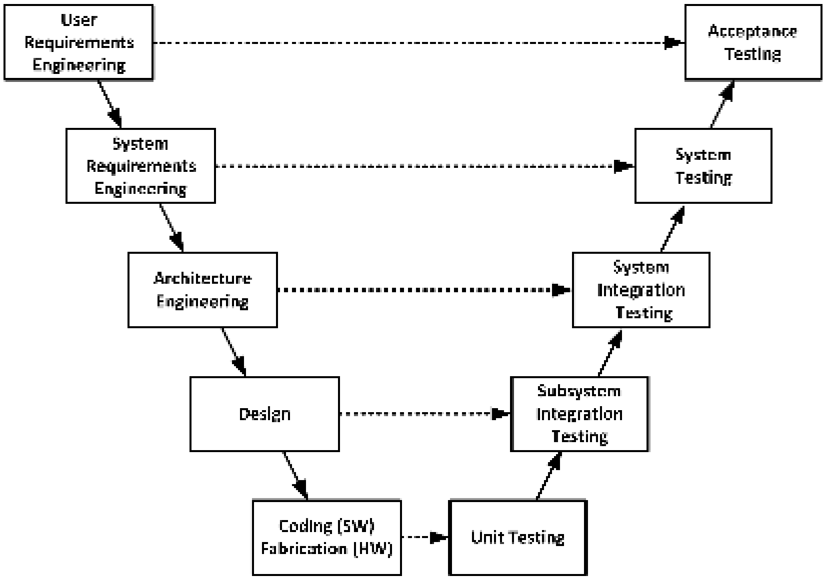


Figure 3-16 - Traditional Systems Engineering V-Model (Firesmith, 2013)

The V-Model follows a design process that begins with the requirements, moving from a high-level design view to sub-system and eventually component level design. Throughout this, the specifications evolve and become more concrete over the process.

USPs

The primary draw of this model is the validation sequence; the horizontal lines that trace from the right side of the V to the left represent the validation links. The element on the right, e.g., System integration testing, is directly validated against the requirements from Architecture Engineering. This means that the system is validated against system requirements, sub-system is validated against sub-system requirements and so on. This is simplistic but ensures that validation occurs on every level, improving product quality from the bottom up. General applicability is an advantage in the use of this model.

Theoretical validity and use

The V-Model is difficult to trace back to its roots, supposedly coming from the Bundeswehr (German Army) in 1992, and variations spawned afterwards. (Der Beauftragte der Bundesregierung für Informationstechnik, 2018) Despite its commitment to validation, it does not tie itself with any methods, thus organisations have taken to filling in that niche using variations such as V-Modell XT (Bundesrepublik Deutschland, 2004). This is both a burden and a boon; it allows organisation managers to utilise their own methods with the model, the price is that these methods are not particularly suited or optimised to the V-Model.

3.3.3 BS 7000

Overview and structure

The British Standards BS 7000 model is a product design methodology that is designed as a baseline standard for building development in Britain. It is broad in its scope and low in detail, thus is applicable as a general design process. (BSI, 2013)

The model, shown in Figure 3-17 is grounded in French’s design model, although it lacks an iterative cycle on any stages. It’s broken down into four stages.

- Motivation
- Creation
- Operation
- Disposal

The “Motivation” stage covers the project trigger, the customer’s demands and the feasibility study. “Creation” covers the design and manufacturing elements of the process, but does not include any iterative steps. “Operation” covers the distribution, logistics, and use of the product. “Disposal” covers post-use scenarios.

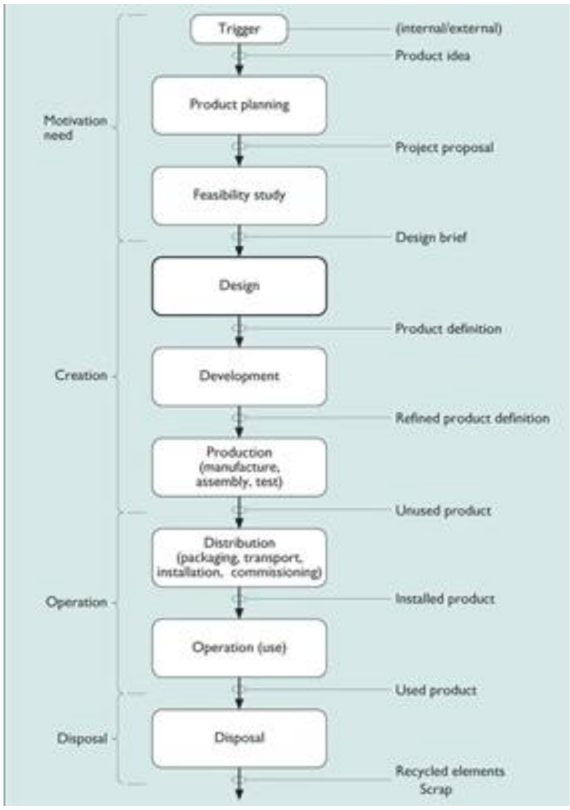


Figure 3-17 – BS 7000 (BSI, 2013)

USPs

BS 7000 uses feasibility studies and maps operation and disposal of the product, which is rare in product development models. The model is simple and broad, allowing a large range of design applications, however the model lacks some key properties preventing it from being utilised in complex systems. The lack of iterative design and concurrency support make this model a hard sell for anything more complicated than domestic products. Additionally, this means that review milestones and optimisations are not supported.

Theoretical validity and use

Use cases are not stated, but the model has served as the basis for many other improvements, such as Pahl and Beitz. (Pahl & Beitz, 1996)

3.3.4 Mechatronic Design Process model

Overview and Structure

Yan and Zante (Yan & Zante, 2010) developed the Mechatronic Design Process (MDP) model to approach mechatronic design in a holistic, generalist manner. The model focuses on function and life cycle issues that appear in the design process.

The MDP model, shown in Figure 3-18, is based on French's model (French, 1985) and is influenced by the author's other works. (Borg, Yan, & Juster, 2000) (Yan & Sharpe, 1994) MDP includes features that make the model suitable for mechatronic design and has three key stages.

- Market Research
- Conceptual system design
- Detail system design

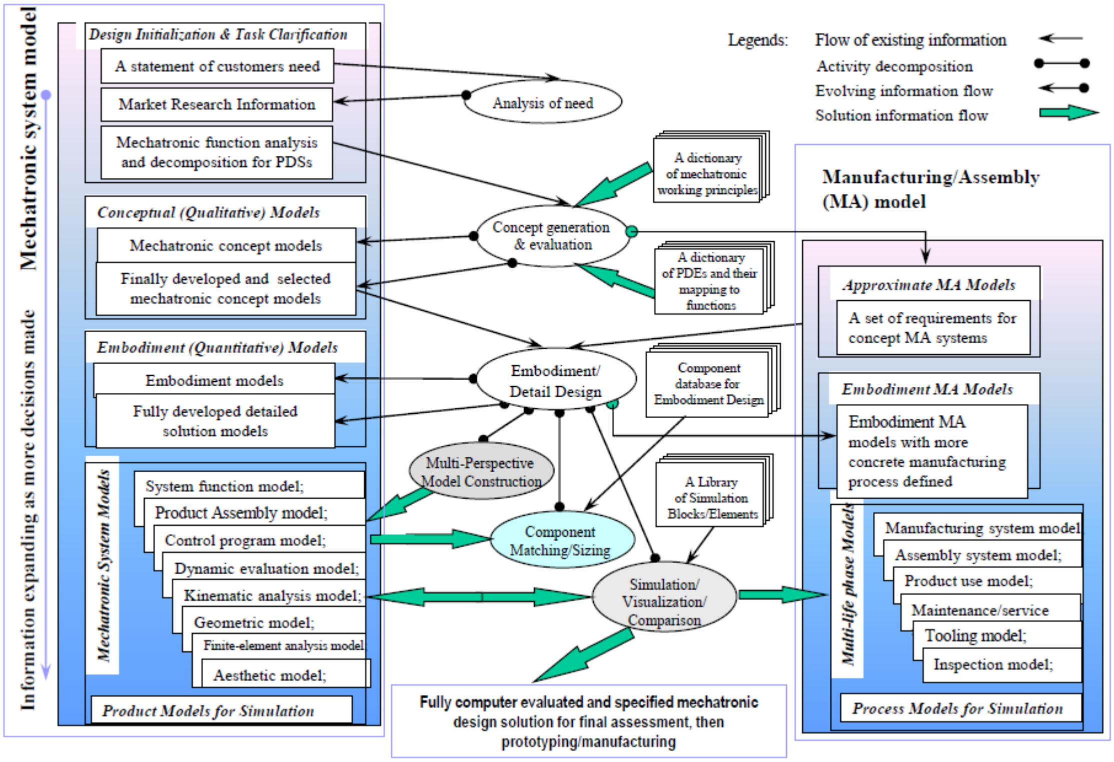


Figure 3-18 - MDP model (Yan & Zante, 2010)

The “Market research” stage maps need analysis, from generating system requirements, transforming them into specifications, benchmarking existing designs and performing function analysis. The “Conceptual system design” stage is standard including concept generation, selection, and refinement. The “Detail system design” stage has a unique approach to validation.

USPs

The model incorporates multi-perspective modelling and focuses on virtual means of design validation. Another novel aspect of the model is the “System model” and “Manufacturing/Assembly” model output columns. The methodology relies on a series of outputs in the form of product models, making this a “model-based” design process. A model-based design process focuses on evaluation through model-making and mitigates many challenges faced in design, such as prototyping, environmental simulation and iterative design. This process requires the use of concurrent engineering to work effectively. Without it, multi-perspective modelling would be too complex and time consuming to add value to the design.

Theoretical validity and use

The MDP model is used in a case study, where the authors show that specific design problems can be solved with the combinatorial analysis of multiple design models. It also promotes the use of function diagrams to map the system. The objective-based nature of the model allows suitable pairing with methods that achieve that outcome; some are specified in the documentation.

3.3.5 Pahl and Beitz

Overview and Structure

Pahl and Beitz (Pahl & Beitz, 1996) had improved design industry with their technical book covering the engineering design process. It uses a foundational principle perspective to focus on the theory and use of their design methodology. Pahl and Beitz' model, shown in Figure 3-19, follows the design process from task clarification to design hand-off. Their model features stage-level objectives and iterative improvements on the product and specification.

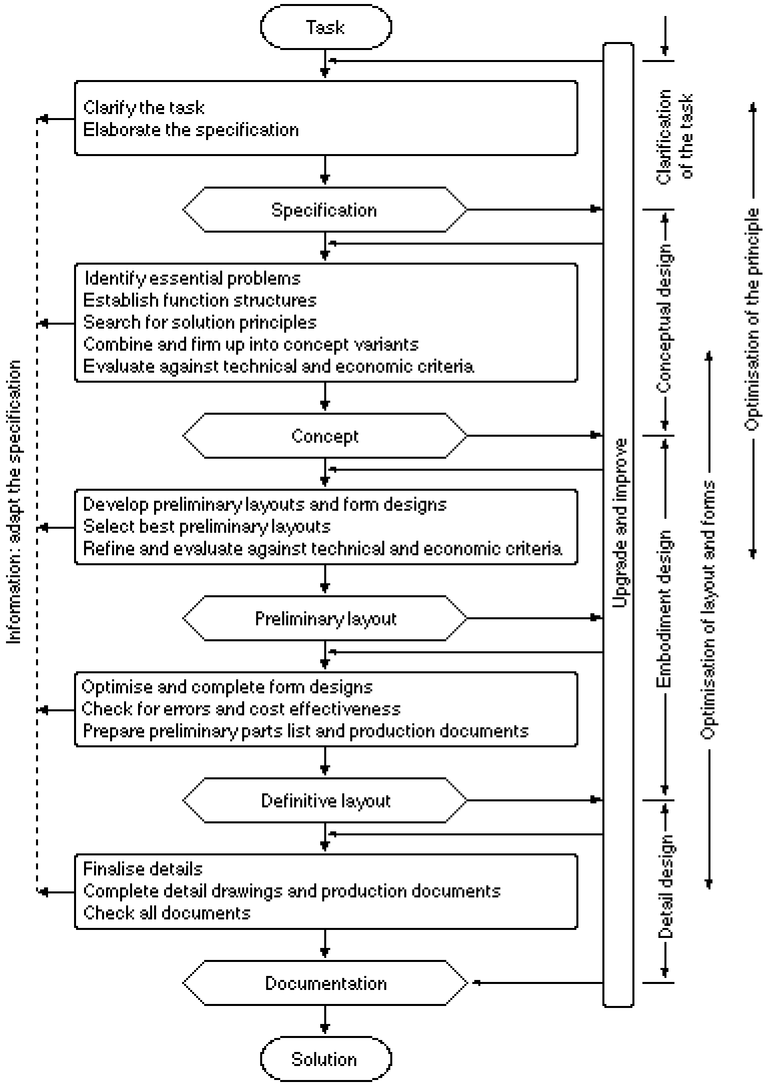


Figure 3-19 - Pahl and Beitz model (Pahl & Beitz, 1996)

USPs

The key aspect of the model is the systematic approach to design engineering, a much needed formulaic and definitive answer to the design problem. Their model is flexible enough to address a wide range of applications but is not too generic. The objective-focused nature of the model allows engineers some freedom to specify methods, so long as they achieve the deliverable needed for that task. The authors suggest methods, such as Failure Modes and Effects Analysis (FMEA) and Quality Function Deployment (QFD) but understand the value in freedom of choice.

Theoretical validity and use

The theoretical robustness of the process is hinged upon the structure and context given in the core work, which aids the adoptability of the model. Its extensive use in industry and academia may be a result of the depth and thoroughness of the literature. Much like Pugh, the authors go into detail about the model's application and provide case studies as example use cases.

3.3.6 Andrews’ comprehensive ship design methodology

Overview and Structure

Andrews (Andrews, 1998) has a very significant piece of work in complex systems, despite being written before computers took hold of design management. The author proposes a comprehensive view of the ship building process that can be used flexibly in other complex systems. Although unnamed, for the purpose of the thesis the methodology will be called Andrews’ Complex Systems Design Methodology (ACSDM), shown in Figure 3-20. The model is a high-level representation of all aspects of ship building from a project standpoint. The model consists of a combination of the author’s other models in a single condensed form. The models consist of the ship synthesis model, warship sizing process, ship design process and tool considerations.

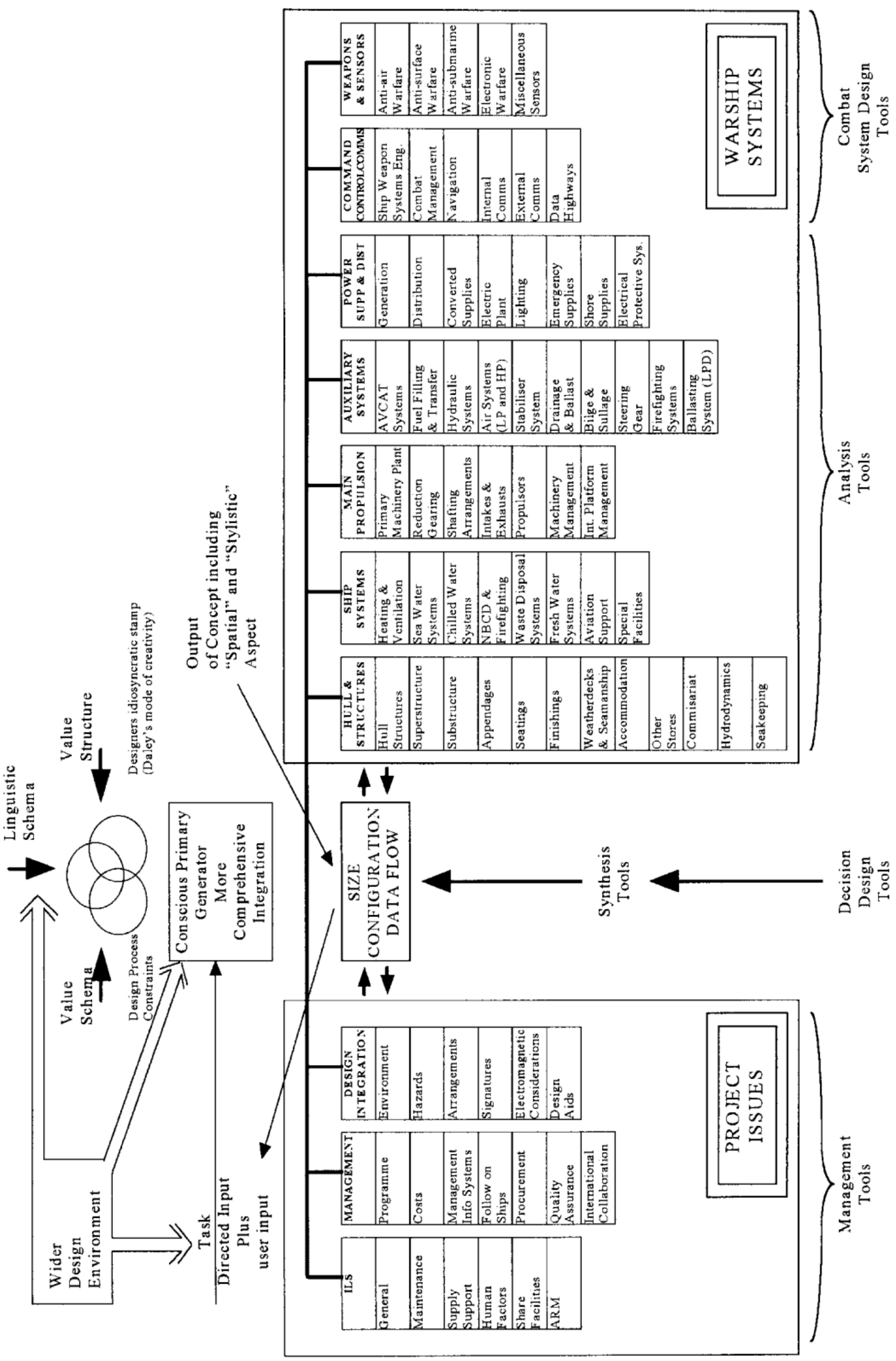


Figure 3-20 - Andrews' comprehensive ship design methodology

USPs

Andrews' work was generated just before the emergent widespread use of computer systems in all facets of the design process. The work proposes a creative design process using SUBCON, which Andrews refers to as a "building block synthesis" design process. This is known now to be a "modular design" method, where sub-system of the vessel becomes a functional building block. The engineer can remove pieces as necessary to envelope these elements in the structure of the vessel. This modularity was novel then, and is now commonplace in ship design, along with the CAD-centric design tasks.

Another novelty in the research comes from the comprehensive view of the ship design process. This model encapsulates most considerations for engineers during the process. Tools, techniques, design considerations and other models are compressed into one graphic. This sacrifices fidelity of the model in favour of generality and requires a working knowledge of each piece of the model from the author's work to fully utilise.

Theoretical validity and use

This work is an all-encompassing view of the ship design process at high level, which requires the engineers to already understand the low level. ACSDM has a very strong theory background, rooted in both academia and industry, representing the intended problem. The strength in its flexibility is that it can be applied to almost any complex engineering field when modified, as modular design is common in other disciplines.

3.3.7 Comparative review

These methodologies were reviewed to establish their key features, demonstrate how they satisfy the methodology requirements and show what makes them unique or useful. The shared traits of successful models can be investigated, and beneficial characteristics can be identified. Through analysis of the methodologies presented, some key success drivers were identified.

Robust origin literature

Having a concrete literature source to back up the design of the methodology is a crucial element in its success. It directly addresses industry concerns regarding verification and validation and serves as an academic source of information. V-Model appears to be an exception to this, despite organisations creating their own source literature for their variations.

User manual and teaching tool

The source literature can also be utilised as a user manual for the methodology. It can be used as reference material for the engineer who wishes to understand more of the in-depth content, or as a manager’s tool for decision making. The literature behind the methodology will aid in teaching the methodology using exercises, promoting learning through positive stimuli and practical work.

Simplistic modelling

Visual representations of the model should be easy to interpret, allowing the user to understand high-level information just by studying the model. The detail content can then springboard off this basic understanding to help accelerate the learning process.

Comprehensive representation

The methodology should fully represent the relevant scope of the design process. In commercial product design this may include sales, in ship building this will include through-life support, in spacecraft this will include disposal and decommissioning. Many methodologies offer a limited window of the design process, which is not reflective of the nature of engineering design in a modern context and is not suitable to complex systems.

Objective driven tasks

Tasks that offer flexibility in the choice of method tend to allow degrees of freedom for designers to make superior decisions. If constraints are required, a task can introduce necessary limitations by focusing on the output of the task rather than the method. This way, the designer is free to use the method they are most confident in, and it also allows organisations to implement their own standards and methods.

Iteration

Iterative cycles in the refinement and evaluation procedures of methodologies aid the designer by forcing them to perform several quality passes on their work. It assists spotting and addressing faults before costly changes are made. It gives rigidity to the verifiability of the design, operating like a continuous improvement process.

Concurrency support

Concurrent engineering principles are important for complex projects. Methodologies generally specify if concurrency is an element in their model, but it may also be possible to optionally support concurrency. Some methodologies require concurrency and cannot operate without it.

Requirements driven design

Cantering the design process to the requirements is an important aspect for maintaining product quality. A well evolved and validated set of requirements forms the basis of design decisions, and acts as a validation reference for the product. By ensuring requirements are correct, legible, and well defined, it also allows the product to follow suite.

3.4 Chapter 3 summary

The aim of chapter 3 was to define the thesis problem, its scope and develop the foundations of a potential solution.

The initial “market research” investigated the engineering design methodology anatomy, looking at design techniques, modern challenges for methodologies research opportunities identified in Chapter 2. It was found that methodology design is much like the engineering design process, starting with exploring the idea and research, generating requirements and ideation, iterating the design through evaluation, and communicating the methodology.

An investigation into existing design methodologies revealed some desirable and avoidable properties for methodologies. These properties were summarised as requirements, which are used in the next chapter to construct a methodology requirements document.

It was determined that the MDP model is a good basis for a new design methodology as it embodies a solution to the problem areas identified. It is an academic model; it is designed with mechatronic and complex systems in mind and it has a novel focus on multi-perspective modelling.

In the next chapter, the research from the previous two chapters were amalgamated and processed to create a requirements document called “Requirements for engineering design methodologies”.

Summary at a glance

- Researched specific strategies to deal with 6 opportunity areas within the real of space system engineering
- Solution to take the form of three things:
    1) A set of requirements drawn up for engineering design methodologies
    2) An engineering design methodology based on those requirements
    3) A guide for verifying and validating design methodologies that can be standardised
- Studied existing methodologies and literature for recommended traits
- Studied modern engineering design techniques and methods

Next…

- Recommendations assembled from research performed in Chapter 3
- Composed these recommendations and findings into a set of requirements called the Methodology Requirements Document

Chapter 4

Requirements definition

Using reviews and observations throughout the literature research, a series of design methodology recommendations were devised in Chapter 3. In this chapter, a design process is defined and these recommendations were refined, combined, and contextualised to generate robust design requirements. This list of requirements was named the “Methodology Requirements Document”. These were linked to illustrate dependencies and relationships between requirements in a diagram called “Relationships between requirements for engineering design methodologies”.

A total of 79 recommendation items were identified from literature, which were transposed into a list of 83 requirements under 19 categories.

These requirements were generated to use as the basis for a new engineering design methodology defined in Chapter 5.

In this chapter:

- **Recommendations for engineering design methodologies**
- **Requirements for engineering design methodologies**

4.1 Recommendations for engineering design methodologies

Cross’ design process model, shown in Figure 3-1, was the basis for the design process used in this thesis. The simplicity of Cross’ model allowed flexibility while the necessary procedure for designing methods was trialled.

This project was triggered by determining the market need, which was done in Chapter 2. In Chapter 3 the problem was defined, and the recommendations were determined, which were obtained from literature and the review of existing methodologies. These recommendations were combined into summary shown in Table 4-1.

Requirements	#
Requirements on Design Methodologies (R) (Keller & Binz, 2009)	19
Industry adoption barriers (I) (Badke-Schaub, Daalhuizen, & Roozenburg, 2011)	11
Complex systems requirements (CS) (Melville & Yan, 2016)	4
Novice engineer needs (NE)	2
Space specific considerations (SS)	4
Lack of methodology validation/verification and utilisation of research (MV)	2
Modern day requirements (MD)	3
Validation Square Validity requirements (VS) (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000)	6
Total Requirements	***51***
Specifications	#
10 commandments (C) (Birkhofer, Kloberdanz, Berger, & Sauer, 2002)	10
Pahl and Beitz rec. (PB) (Pahl & Beitz, 1996)	10
Methodology review suggestions (MR)	8
Total Specifications	***28***

Table 4-1 - Number of requirements and specification recommendations from literature

Each of the literature pieces are compressed into their own coded categories. A total of 51 desirable traits were identified and 28 specification elements along with them. The core recommendations were specified in Table 4-2, the contextual recommendations specific to this thesis are marked in Table 4-3. The additional specification items are listed in Table 4-4. All these items are codified for easy reference.

(R)	*(I)*	*(VS)*	*(MD)*
R1. Validation R2. Verification R3. Innovativeness R4. Competitiveness R5. Objectivity R6. Reliability R7. Validity R8. Comprehensibility R9. Repeatability R10. Learnability R11. Applicability R12. Efficiency R13. Effectivity R14. Problem Specificity R15. Handling Complexity R16. Problem solving Cycle R17. Structuring R18. Compatibility R19. Flexibility	I1. Missing Validation I2. Unknown impact I3. Different forms of designing not being accounted for I4. Inadequate advertisement of methods I5. Inappropriate rep. of method I6. Addresses knowledge, not application I7. No differentiation along design principles I8. Low flexibility I9. Time consuming I10. Lack of support from management I11. No adaption to different situational conditions	VS1. Accepting the constructs validity VS2. Accepting method consistency VS3. Accepting the example problems VS4. Accepting the usefulness of the method for some example problems VS5. Accepting that usefulness is linked to applying the method VS6. Accepting usefulness of method beyond example problems	MD1. IT systems MD2. Specialist products MD3. Knowledge and information management

Table 4-2 – Basic requirements recommendations matrix

(SS)	*(MV)*	*(NE)*	*(CS)*
SS1. Expensive full-scale prototypes SS2. Late integration of systems SS3. Environmental emulation is difficult SS4. Human error accountability	MV1. Under-utilised design research MV2. No standards for verification and validation	NE1. Need for understanding own needs NE2. High level stratagem	CS1. Complex design management CS2. Complex knowledgebase CS3. Increased uncertainty and risk CS4. Design evaluation and non-destructive testing

Table 4-3 – Contextual requirements recommendations matrix

(C)

C1. Design is not design
C2. Times have Changed
C3. Focus on the methods for best processes
C4. Don’t forget Organisation
C5. Methods have a processable result
C6. Users use methods
C7. Teach theory
C8. Design is difficult enough
C9. Need for software tools
C10. Get on with design methods

(PB)

PB1. Allow a problem-directed approach
PB2. Foster inventiveness and understanding
PB3. Be compatible with concepts, methods and findings
PB4. Not rely on finding solutions by chance
PB5. Facilitate the application of known solutions
PB6. Be compatible with electronic data
PB7. Be easily taught
PB8. Reflect the findings of cognitive psychology and modern management science
PB9. Ease the planning and management of teamwork
PB10. Provide guidance for leaders

(MR)

MR1. Robust origin literature
MR2. User manual and teaching tool
MR3. Simplistic modelling
MR4. Comprehensive representation
MR5. Objective driven tasks
MR6. Iteration
MR7. Concurrency support
MR8. Specification driven design

Table 4-4 - Specifications recommendations matrix

These suggestions from literature in Table 4-2 are treated as basic requirements. Niche requirements that are specific to the problem areas outlined in this thesis, outlined in Table 4-3 are combined with this list of basic requirements. The rest of the items, shown in Table 4-4, can provide a means of achieving those requirements.

When combining these requirements into a list, Keller & Binz’ requirements (Ref R#) are used as the headings or categories of requirements, while the rest are sub-requirements. Requirements that overlap are grouped and recommendations that influence each other directly are linked. Using the influence map from Table 3-5, a diagram that maps the causal relationships between recommendations is shown in Figure 4-1.

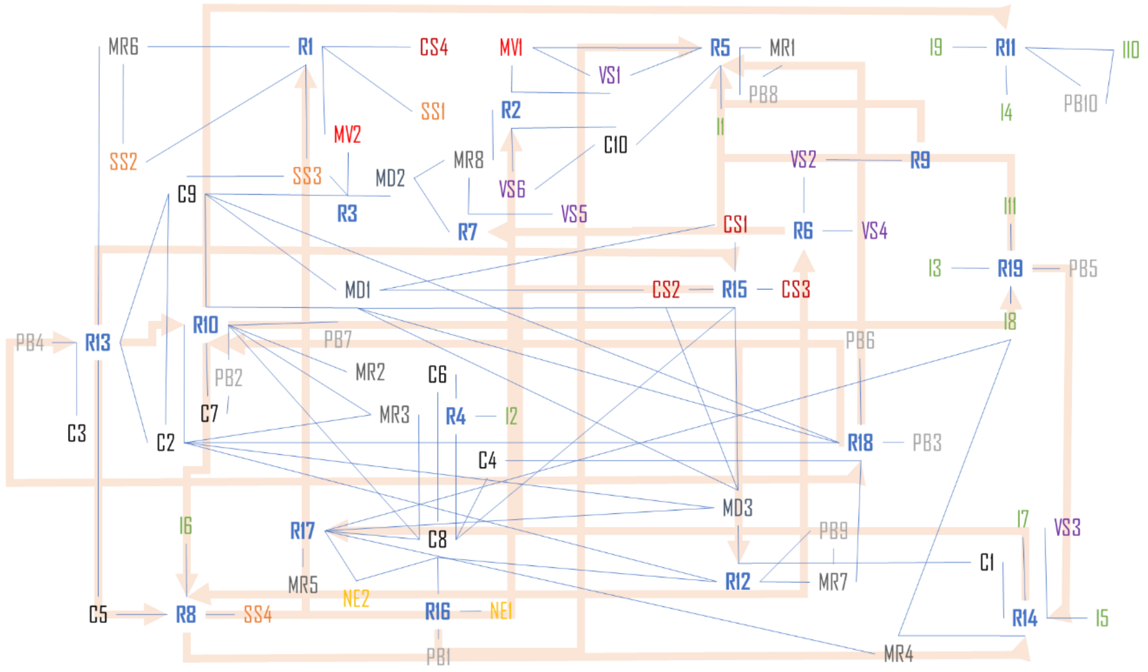


Figure 4-1 – Relationships between requirements for engineering design methodologies

In the above diagram, R1-16 are the central requirement headings, surrounded by related recommendation items. Orange arrows link major requirement groups, and blue ones link sub-requirements. The nature of the relationships means that each element is influenced by one another in some form.

Using these links, the findings of the literature review were condensed into a requirements document called "Requirements for engineering design methodologies", using the methodology requirements (R#) as headings. The following section is a requirements document demonstrating the literature recommendations and how these were morphed into a document that drives the formulation of the design methodology.

4.2 Methodology Requirements Document

Using the information generated from the research outlined in this chapter, all the requirements were compiled into the document bellow, named the “Methodology Requirements Document”. The document is created using requirements linking to categorise the information, like in Pugh’s PDS format. This format is a mirror of Pugh’s, not only as a homage but also as a convenient tool for communication.

Alongside each heading are the identification codes for the requirements. These codes show which of the original recommendations are being embodied in the requirement. For example, code CS4 was a complex systems industry specific requirement that called for “non-destructive testing”. This is satisfied under R1.2.2 by including “Virtual prototyping” support in the design methodology.

R1. Validation (R1)

R1.1 Do things right

- R1.1.1 The methodology shall be tested against a validation standard (MV2)
- R1.1.2 The methodology shall undergo iterative evaluation (MR6)
- R1.1.3 The methodology shall satisfy end user requirements (R1)

R1.2 Testing

- R1.2.1 The methodology shall accommodate non-destructive testing (CS4)
- R1.2.2 The methodology shall accommodate virtual prototyping (SS3)
- R1.2.3 The methodology shall accommodate iterative, early-stage component testing (SS2) (MR6)
- R1.2.4 The methodology shall accommodate sub-assembly testing (SS1)
- R1.2.5 The methodology shall accommodate multi-perspective modelling (SS3)

R2. Verification (R2)

R2.1 Do the right things

R2.1.1 The methodology shall be designed using a design process (MV1) (VS1) (R2)

R2.1.2 The methodology shall be designed from the requirements (MR8)

R2.1.3 The methodology shall evolve from use-case feedback (C10) (VS6)

R3. Innovativeness (R3)

R3.1 Unique Selling Points

R3.1.1 The methodology shall include and develop new validation standards (MV2) (R3)

R3.1.2 The methodology shall be developed in the context of complex space system design (MD2) (R3)

R3.1.3 The methodology shall be developed to focus on multi-perspective modelling (SS3) (C9) (R3)

R4. Competitiveness (R4)

R4.1 Industry equivalency

R4.1.1 The methodology shall be evaluated by the relative performance against a benchmark (I2) (R4)

R4.2 Adoptability

R4.2.1 The methodology shall explicitly state its potential impact (I2)

R4.2.2 The methodology shall convey its efficiency and effectiveness for upper management (C6)

R4.2.3 The methodology shall convey the efforts in implementation for middle management (C6)

R4.2.4 The methodology shall convey its ease of use for engineers (C6) (C8)

R5. Objectivity (R5)

R5.1 Systematic design

R5.1.1 The methodology shall follow a systematic design process (VS1) (R5)

R5.2 Scientific origins

R5.2.1 The methodology shall convey its validation procedure (I1) (R5)

R5.2.2 The methodology shall generate a Requirements document from literature (MV1) (R5)

R5.2.3 The methodology shall be grounded on state-of-the-art research (PB8) (MR1) (R5)

R5.2.4 The methodology shall evolve from heuristic feedback (C10)

R6. Reliability (R6)

R6.1 Consistency in delivery

R6.1.1 The methodology shall operate similarly in each instance (VS2) (R6)

R6.1.2 The methodology shall deliver consistent results (VS2) (R6)

R6.2 Consistency in analysis

R6.2.1 The methodology shall work with design problems that are comparable (VS4)

R7. Validity (R7)

R7.1 Promises vs Delivery

R7.1.1 The methodology shall adopt requirements focused design (MD2) (MR8) (R7)

R7.1.2 The methodology shall demonstrate that it is responsible for output delivery (VS5)

R8. Comprehensibility (R8)

R8.1 A priori justification

R8.1.1 The methodology shall address its application as opposed to its knowledge (I6)

R8.1.2 The methodology shall provide a basic understanding of its decisions (R8)

R8.2 Posteriori justification

R8.2.1 The methodology shall accommodate design reporting and error checking (SS4)

R8.2.2 The methodology shall accommodate post-use documentation (C5)

R9. Repeatability (R9)

R9.1 Adherence to methodology cross-instance

R9.1.1 The methodology shall be tolerant to slightly different circumstances (VS2)

R9.2 Comparability of tasks

R9.2.1 The methodology shall keep activities consistent in cross-instance application where possible (VS2) (R9)

R9.3 Comparability of outputs

R9.3.1 The methodology shall have its outputs remain consistent in cross-instance application where possible (VS2) (R9)

R10. Learnability (R10)

R10.1 Ease of learning

R10.1.1 The methodology shall support methods and tools (MD1) (C2) (C9)
R10.1.2 The methodology shall adopt a top-down approach to training (PB7)
R10.1.3 The methodology shall adopt a practical teaching approach to methods (C7) (R10)
R10.1.4 The methodology shall teach its low-level functionality (PB2) (C7)
R10.1.5 The methodology shall come with a manual (MR2) (R10)
R10.1.6 The methodology shall represent complex concepts with models (MR3) (C8)

R10.2 Willingness of learning

R10.2.1 The methodology shall adopt a positive reinforcement teaching strategy (C7)
R10.2.2 The methodology shall have shared materials to promote discussion (MR2) (R10)

R11. Applicability (R11)

R11.1 Applicable to organisation

R11.1.1 The methodology shall be quick and efficient to implement (I9) (R11)
R11.1.2 The methodology shall support management tools (I10) (PB10)

R11.2 Applicable to problem

R11.2.1 The methodology shall advertise its methods (I4)

R12. Efficiency (R12)

R12.1 Resource efficiency

R12.1.1 The methodology shall accommodate resource allocation and planning (C4) (C8)

R12.1.2 The methodology shall disincentivise excessive resource expenditure (R12)

R12.2 Personnel efficiency

R12.2.1 The methodology shall accommodate personnel allocation and planning (C4) (C8)

R12.3 Effort expenditure

R12.3.1 The methodology shall accommodate data management tools (MD3) (C2)

R12.3.2 The methodology shall accommodate concurrent engineering principles (PB9) (MR7)

R12.3.3 The methodology shall map design resource flow (C1)

R13. Effectivity (R13)

R13.1 Perceived effectiveness

R13.1.1 The methodology shall produce design solutions through its adherence (PB4)

R13.1.2 The methodology shall accommodate CAD (C2) (C9)

R13.1.3 The methodology shall recommend best-in-class methods by default (C3)

R13.1.4 The methodology shall comprise of methods with measurable outputs (C5)

R13.2 End goal vs actuality

R13.2.1 The methodology shall contain iterative validation milestones (MR6) (R13)

R14. Problem Specificity (R14)

R14.1 Definition of scope

R14.1.1 The methodology shall differentiate between its design principles (I7)

R14.1.2 The methodology shall provide representation of its methods (I5)

R14.1.3 The methodology shall provide representation of relevant non-design factors (C1)

R14.1.4 The methodology shall provide a comprehensive overview of the design process (MR4)

R14.1.5 The methodology shall specify applicable design circumstances (R14) (VS3)

R15. Handling Complexity (R15)

R15.1 Task translation

R15.1.1 The methodology shall break tasks into simple objectives (C8) (R15)

R15.1.2 The methodology shall impose useful limitations on design (CS3) (R15)

R15.2 Complex design management

R15.2.1 The methodology shall accommodate PLM systems (CS1) (MD1) (MD3) (C2) (C9)

R15.2.2 The methodology shall accommodate knowledge and data management tools (CS2) (MD1) (MD3) (C9)

R16. Problem Solving Cycle (R16)

R16.1 Schema

R16.1.1 The methodology shall communicate the designer’s knowledge requirements (NE1) (R16)

R16.1.2 The methodology shall adopt a problem-oriented approach (PB1)

R16.1.3 The methodology shall break down the problem structure (C8) (R16)

R17. Structuring (R17)

R17.1 Subdivision

R17.1.1 The methodology shall have a high level stratagem (NE2) (C8) (R17)

R17.1.2 The methodology shall partition information while maintaining transparency (MD3)

R17.1.3 The methodology shall make tasks objective-focused (MR5)

R17.2 Alternatives

R17.2.1 The methodology shall have a partially modular construction (R17) (I8) (MR4)

R18. Compatibility (R18)

R18.1 Intra-Methodology

R18.1.1 The methodology shall be compatible with novel methods and findings (PB3) (R18)

R18.2 Organisational

R18.2.1 The methodology shall accommodate IT systems (MD1) (PB6) (C2) (C9) (R18)

R18.2.2 The methodology shall accommodate concurrent and centralised design (MR7)

R18.2.3 The methodology shall be applicable to organisations within the target scope (C4) (R18)

R18.2.4 The methodology shall use a common nomenclature (C4)

R19. Flexibility (R19)

R19.1 Degrees of freedom

R19.1.1 The methodology shall account for different forms of design (I3) (R19)

R19.1.2 The methodology shall specify the extent of its flexibility (I8)

R19.1.3 The methodology shall be able to adapt to project circumstances (I11) (R19)

R19.1.4 The methodology shall accommodate known solutions or legacy designs (PB5)

4.3 Chapter 4 summary

This chapter broke down the 51 requirement recommendations for engineering design methodologies, 39 of which were relevant to methodology design. The remaining 12 were contextually specific to the thesis goal. A further 28 recommended specification elements were found, totalling 79 total recommendations.

These recommendations were linked to map the influence they carry on each other. This model was then used to create a refined requirements document called the Methodology Requirements Document. This document was in the form of Pugh's PDS and provides the information required to act as the source document to develop a new CSE design methodology.

Using the Methodology Requirements Document generated in this chapter, the next chapter constructs an engineering design methodology called the Tiv-Model.

Summary at a glance

- Recommendations for engineering design methodologies from literature were collated
- They were then constructed into Methodology Requirements document
- The document lists 83 requirements, some universal and some specific to the thesis

Next…

- Methodology requirements document used to construct the Tiv-Model
- The Tiv-Model defined as the solution to the problem statement

Chapter 5

Solution definition

Utilising the requirements created in the previous chapter, a new CSE design methodology was developed, named the Tiv-Model. The Tiv-Model is an engineering lifecycle model for use with complex space systems and is built to tackle the industry problems identified in Chapter 2. In this chapter, the model is defined, and the design decisions are justified by linking back to each of the requirements specified in Chapter 5. The novel aspects and potential benefits of the Tiv-Model are also presented here.

In this chapter:

- **The Tiv-Model**
- **Novel aspects and benefits of the Tiv-Model**
- **Requirements satisfaction**

5.1 The Tiv-Model

In Chapter 4 a requirements document was generated containing baseline information for an engineering design methodology. This chapter detailed the embodied methodology and provided design decision justifications based on the requirements.

The design process for the Tiv-Model followed the generic procedure outlined in Figure 3-1. The high-level operation of the Tiv-Model is summarised in a diagram, shown in Figure 5-1.

The Tiv-Model is the outcome of literature reviews about design, methods, and methodologies. It was designed to satisfy several "market" needs:

- To address industry concerns with academic models and increase industry implementation rates,
- To accommodate the challenges associated with modern complex system design, particularly spacecraft design,
- To demonstrate the use of V-Square as a new means of methodology evaluation,
- To amalgamate recent design research findings into a useful state.

The name "Tiv-Model" was derived from the last syllable of the stage names (Qualitative, Investigative, etc) and form the acronym of the three TIV principles to be used as a mnemonic device. The word "Tiv" also loosely represents the shape of the model. This is designed to aid recollection of the model and its primary stages, much like Cross' model. The model is formed around the specification document and developed through literature recommendations. Key features involve iterative design evaluation, system level work breakdown and generating "deliverables" within each phase. It encourages the use of concurrent engineering design principles and can accommodate centralised design. The end of the detail design phase calls for a multi-perspective model, a CAD simulation intended to analyse each disciplinary aspect of the design. Tiv-Model satisfies both academic and industrial needs by using recent research findings to implement efficient and effective design strategy. Tiv-Model was also designed as an example of a use case for the Methodology Requirements Document and the use of the V-Square validation method.

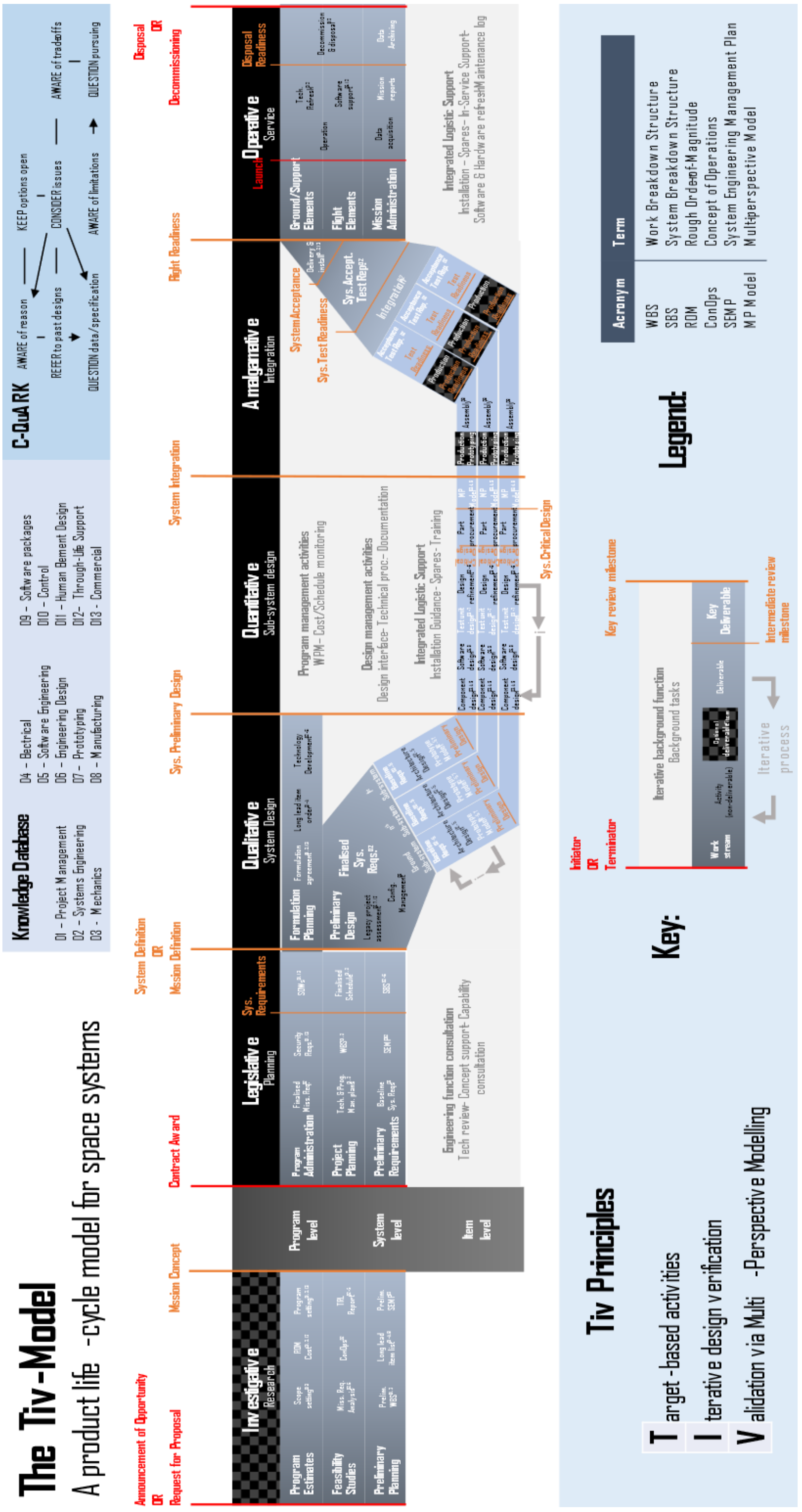


Figure 5-1 - The Tiv-Model

5.1.1 The Tiv-Model at the Macro-level

The Tiv-Model is a collection of methods, shown across several graphics (Figure 5-1, Figure 5-3, Figure 5-10, Figure 5-11, Figure 5-12, Figure 5-14). Each graphic is a representation of the Tiv-Model at a different scale or zoom. These Levels of Detail (LODs) are comprised of three scales: Macro, Mid and Micro level, shown in Figure 5-2. The three scales combine to form the Tiv-Model, partitioning them prevents information overload. Each member of a design project will be interested in a different LOD, for example, organisational leaders will be concerned with the project lifecycle, represented in the macro-level view. Project managers will utilise both the macro and mid-level views. Engineers will familiarise themselves with the mid and micro levels, which contain the problem-solving tools that enable them to complete their tasks.

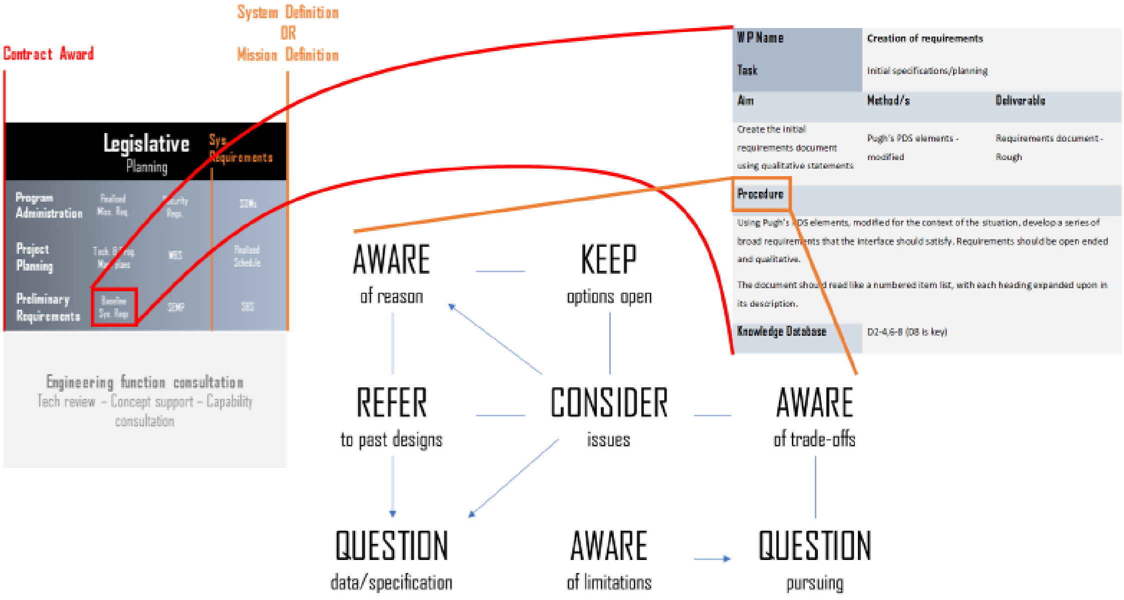


Figure 5-2 - Macro, Mid and Micro LODs

The Macro-level view of Tiv-Model incorporates the product lifecycle. This is the face of Tiv-Model and the first thing people will be introduced to, it is broken down in Figure 5-3. This graphic sacrifices detail for a bigger picture, akin to the TDM, V-Model and other models captured in

Chapter 3. The information available on the macro-level view can be categorised into Stages, Workstreams, Deliverables, Activities, Milestone Reviews, and the System level breakdown.

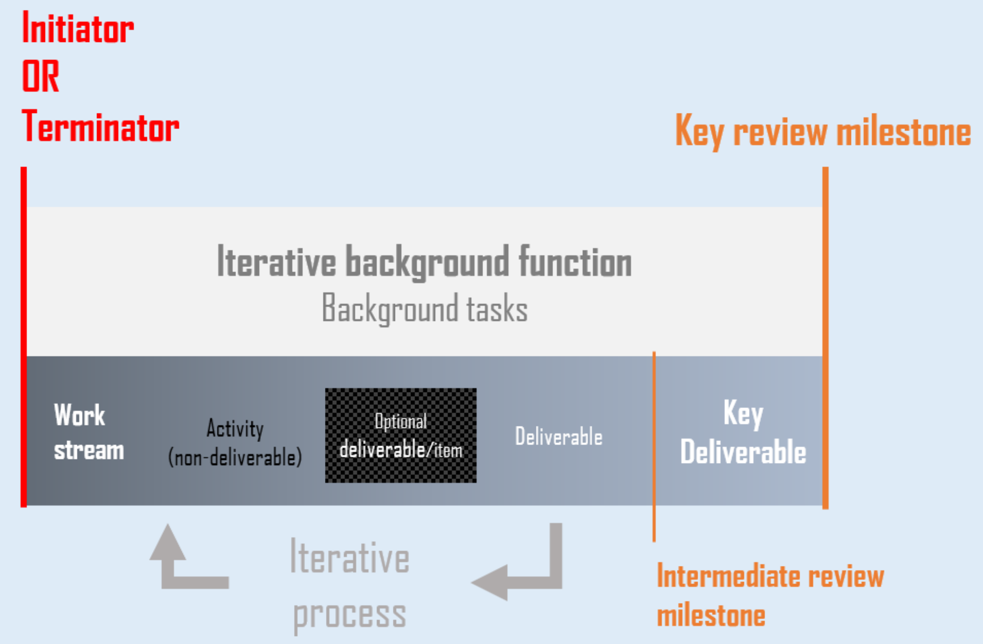
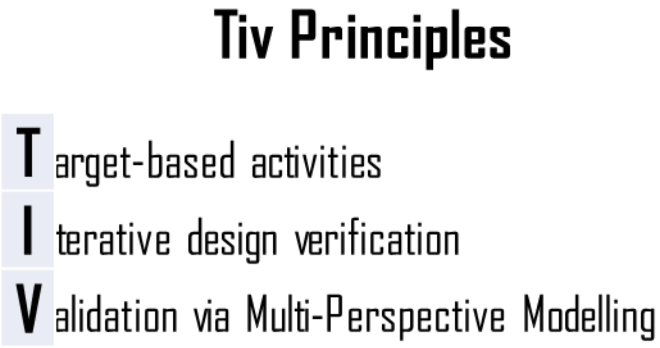


Figure 5-3 - Macro-model Tiv breakdown

The Tiv-Principles

The Tiv-Model functions on three basic principles, each one represented by a letter in the name "Tiv". These Tiv-principles act as a guide for the engineers, to direct the flow of their efforts over the course of the project. The 3 principles are shown in Figure 5-4.



Tiv Principles

T arget-based activities
I terative design verification
V alidation via Multi-Perspective Modelling

Figure 5-4 - Tiv-Principles

Target-based activities

This principle states that whenever a task or activity is performed, the critical aspect is the outcome. The process surrounding its delivery should be based primarily on the requirement of the deliverable at the end of the process. This also means that processes that are done “for process’s sake” are not permittable within the model. Procedures must have a clearly defined and useful purpose.

Iterative design verification

When performing engineering design tasks, cyclical refinement and continuous improvement are two processes that need repeated application. For example, when conceptualising a design, revisit and refine it to improve the quality. Specifically in terms of the model, this refers to the iteration of improvement between Milestone Reviews. The work between these points can be considered iterative for the purposes of refinement. Things are rarely perfectly correct the first time.

Validation via Multi-perspective modelling

The final principle tells the users that the validation of design is best performed via the use of “multi-perspective modelling”. Multi-perspective modelling is a modelling strategy that involves combining the various views of a system (mechanical/electrical/thermal) and creating one single, multi-purpose model. The reason behind this is so that the model considers the knock-on effect each type of load has on the others. For example, the change to mechanical properties of a design due to the thermal load. This can be performed as a thought exercise but can also be performed in depth using some CAD packages, in particular Fusion 360.

Model Architecture

The structure of the Tiv-Model can be represented in several ways, but the name of Tiv-Model is reflected in its high-level architecture. The Tiv-Model borrows many aspects from industry models, namely 3-column model and NASA’s systems engineering process.

System-level breakdown

Near the left of the Tiv-Model is the system level breakdown, shown in Figure 5-5. This breaks work down by how high level it is from the perspective of the system. Halfway up is the System level, which incorporates the scope of work such as requirements definition and testing. Above this is Program level, which encompasses activities that are high level, but outside the scope of engineering, such as project management activities or logistical elements. At the bottom is the Item level, which deals with component-level work and specific tasks like detailing of part drawings. There are levels in between (such as sub-system) that aren’t identified in the text but exemplified by the height of the task on the scale. The height of the task along this scale identifies the level of the work.

Figure 5-5 - Tiv-Model system level breakdown

The “T”, “I” and “V”

The beginning of the Tiv-Model contains the research and contract-based activities, such as mission conceptualisation, tech research and project planning. These stages are grouped into what can be called the “Trigger” stages and they define the “T” in the Tiv-Model, based on the appearance of the stages in the model. This graphic is shown in Figure 5-6.

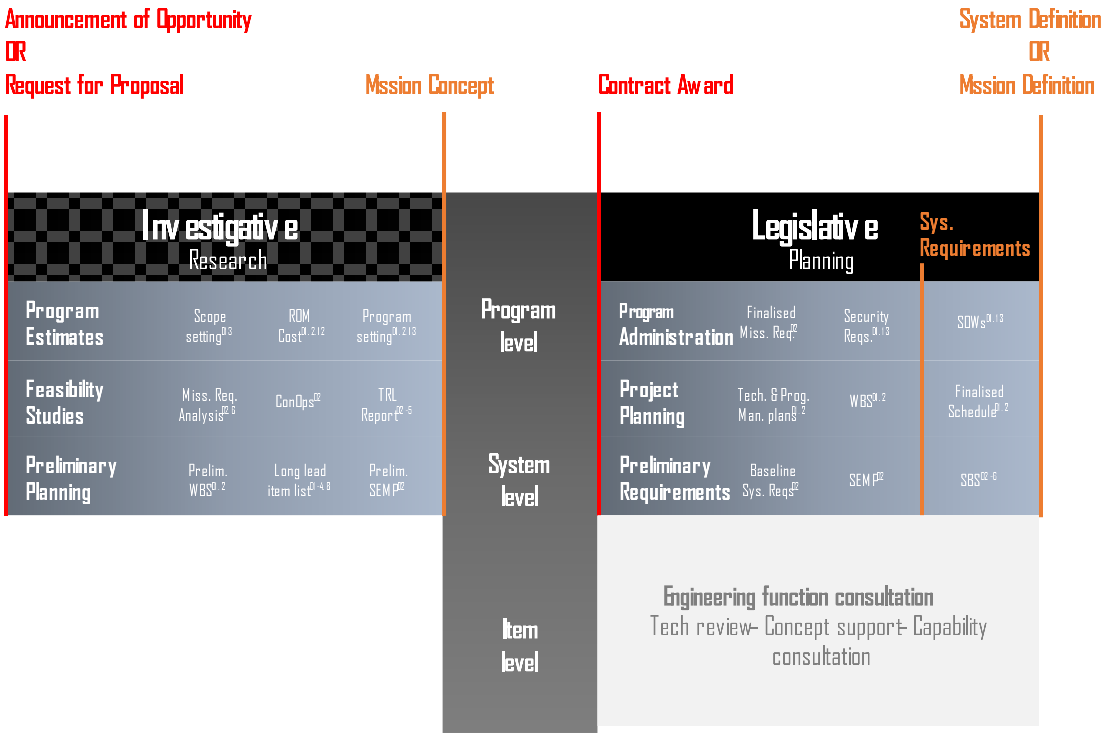


Figure 5-6 - Tiv-Model Trigger stages (The "T")

Tasks that are present throughout the Tiv-Model, that iterate and upkeep the project, are defined as the “Iteration” tasks, represented in Figure 5-7 as the “I”. These items are identified by the light grey backgrounds and are not in focus on the model. This represents the background nature of the upkeep these tasks generate.

Figure 5-7 - The Iterative tasks (The “I")

The final set of tasks, often classified as the development track of activities, represent the "V" in the Tiv-Model as "Validation". These tasks embody most of the engineering work in a project and are generally low-level, including testing. This is shown in Figure 5-8.

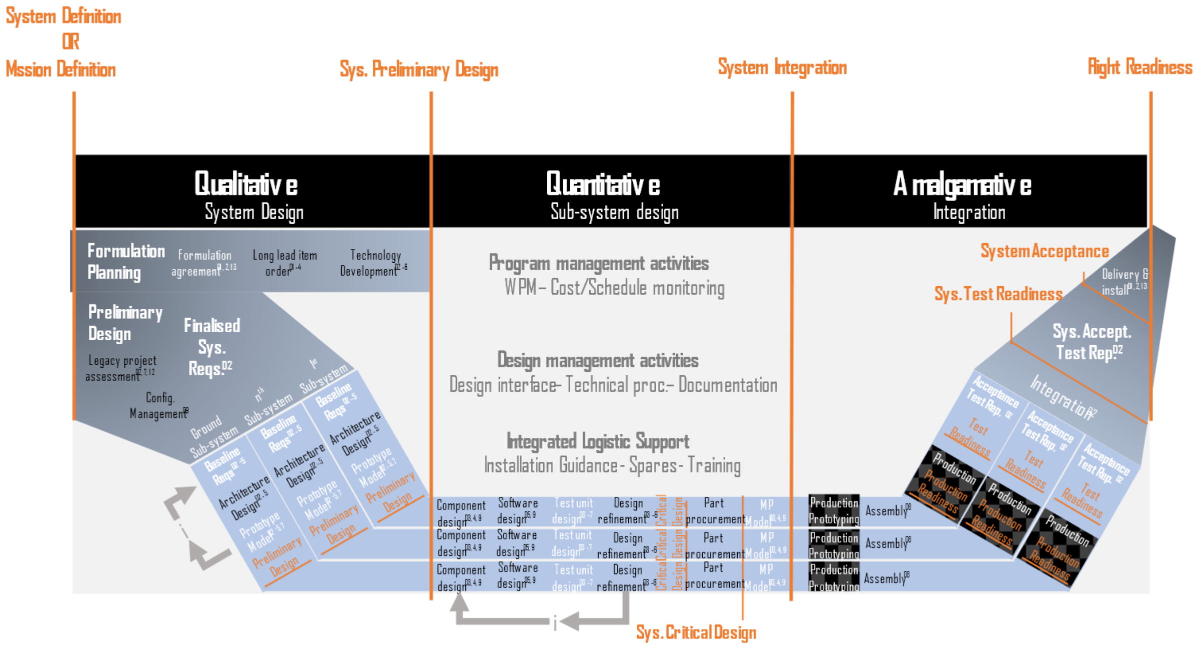


Figure 5-8 - Tiv-Model Validation stages (The "V")

The final stage is not attributed to either of the Tiv-Model letters but includes the operation of the product as part of the process, shown in Figure 5-9.

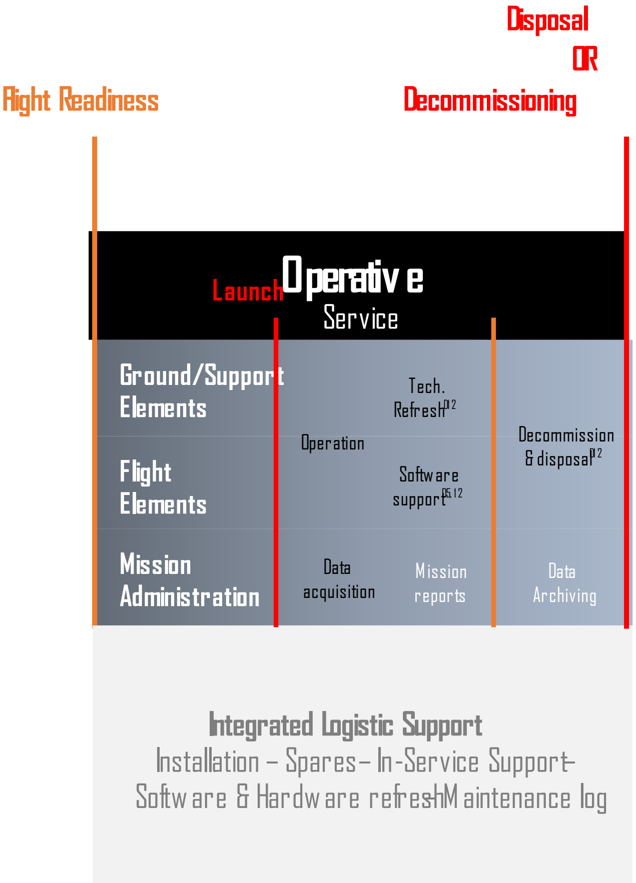


Figure 5-9 - Tiv-Model final stage

Stages and Workstreams

As with every design methodology, the high-level design activities are categorised in stages. The stage name will provide a basic description of the activities that take place. The naming convention of Tiv-Model's stages use a "tive" suffix as a mnemonic device. These stages happen chronologically from left to right and contain several deliverables, categorised by workstream. Workstreams are subdivisions of collective work that follow a general theme within that stage. The "Feasibility Studies" workstream is a valid example, this task is performed in the initial Investigative stage and contains three deliverables that embody the delivery of a feasibility study. Each Workstream has a series of Activities and Deliverables, which are required to be completed around that time within the lifecycle. Once all Deliverables and Activities in a Stage are complete, further work is gated by a Milestone Review which is performed at the end of the stage or in some cases, intermediately within a stage. Deliverables, Activities and Milestones Reviews are explored in detail later, the following sub-sections cover each stage's definition.

Investigative Stage

The Investigative stage is the period where preliminary research is conducted, including the gathering and development of client requirements, the feasibility study and rough planning. This stage is triggered by a Request for Proposal (RFP) or Announcement of Opportunity (AoO). Projects that have established customer requirements and do not require conceptual mission research can forge this stage and instead begin on the Legislative stage. This modularity is discussed later in section 5.3. The customer brief should be formalised in a kick-off meeting, where the system architects and project leads are provided with the mission requirements, objectives, and payload specifications if any, the scope is set in agreement with the customer. From this, the design feasibility studies where the teams establish the project knowledge needs. The program teams develop rough cost projections and preliminary plans. This stage ends with the Mission Concept Review (MCR) before moving to the Legislative stage.

Legislative Stage

The Legislative stage is the timeframe in which the contractual documents are finalised. It continues to baseline the mission and system requirements from the previous stage. The project and technical planning and breakdown structures are finalised here. Once requirements are baselined, an interim System Requirements Review (SRR) takes place. Once this is passed, the schedule is finalised, and the System Definition Review (SDR) takes place. If the mission is manned, this review is replaced with the Mission Definition Review (MDR) instead. This stage generally lasts around 18 months. During this time, at the item level, component engineering teams are on hand to provide consultancy and support for the technical content.

Qualitative Stage

The Qualitative stage embodies the system level design process, with refinement of the system concept. Each of the sub-systems, defined in the architecture from the Legislative stage, are broken down into sub-system requirements. The system requirements are also finalised at this point, and long lead-time items are identified and ordered. Configuration Management begins at this stage and versioning is enforced for developed parts. Concurrent engineering is enacted from this point until the end of the Amalgamative stage, this is because the tasks fall into the sub-system and item level work, shown by the dip in the “V”. After defining, modelling and refinement, each subsystem is subjected to Preliminary Design Reviews (PDR), and after they have all passed the System PDR takes place.

Quantitative Stage

The Quantitative stage continues into the detail design, moving from sub-system to component level. This work embodies the core of the design process, where all disciplines are in action. Program management and documentation are continuous clerical tasks that happen throughout this stage. The mechanical and electrical engineers define the sub-system components and refine their design through an iterative process of evaluation. Early software testing is encouraged. Once in a satisfactory state, each sub-system undergoes a Critical Design Review (CDR) to determine if the subsystem has been adequately embodied. The System CDR follows from this, and procurement can begin for the remaining parts. After this, a multi-perspective model must be delivered for each sub-system to verify the design. If the results are satisfactory, the System Integration Review (SIR) takes place to evaluate the readiness of the design for integration and prototyping. Production of drawn parts will happen before this stage is complete.

Amalgamative Stage

The Amalgamative stage is where iterative testing takes place on every level. Sub-system assembly and testing takes place, which includes production prototyping if there are multiple system sets. In this case, the Production Readiness Review (PRR) is required. The Test Readiness Review (TRR) is required before the sub-system tests. Once each has passed, the system is integrated, commissioned, and subjected to the System TRR. This is the gateway to the System Acceptance Test and Review, which is one of the key milestones in the project. When ready, the system is delivered to the customer, any remaining assemblies are conducted before the Flight Readiness Review (FRR) which evaluates the suitability for launch.

Operative Stage

The Operative stage concludes all design and manufacturing work and moves into logistics and support. This stage begins with the preparations for and commitment to launch. After launch,

Launch and Early Orbit Phase (LEOP) begins, and deployment of structures is underway. Following on some basic tests, the system is ready, and the mission can begin. Maintenance on the space system within the operation period may include patches, operator training and possibly On-Orbit Servicing. Ground station elements can be supported in a simple manner. During this phase, mission and maintenance reports are iterative. After mission completion, decommissioning disposal is preceded by the Disposal Readiness Review (DRR). When passed, preparations are made to dismantle and deorbit the system, repurpose the ground station equipment and publish the post-mission report. All data is archived, and lessons learned are documented.

Activities and Deliverables

Along the Workstreams of the Tiv-Model, white text items represent Deliverables and black text items represent Activities. Deliverables and Activities are the lowest level of plannable action that can be taken at the project level, and the Tiv-Model shows the critical items across the workstream path. Deliverables are items or information that are the resultant output of tasks, they can be in the form of documents, CAD files, drawings, contracts, and so on. Activities are tasks that have a function but do not necessarily deliver a measurable item. These two items are key to the advancement of the project. This means that deliverables can come in many forms; most commonly they are manifest as discrete computer files, or physical documents. These files also come in genres, such as reports, CAD files, data dumps, orthographic drawings, signed agreements, and so on. The purpose of Deliverables is that they house information that is pertinent to the continued development of the project. Deliverables drive the methods used in the design process. This is the embodiment of the “T” in the Tiv-Principles.

Milestone Reviews

Milestone reviews are gateway checks that ensure the work before it has been conducted and completed satisfactorily. Reviews, highlighted in orange on the Tiv-Model, can happen in the middle of a stage, or at the end, signalling stage completion. Milestones Reviews in Tiv-Model follow the standard structure used by NASA and AIAA. (NASA, 2020) Some tasks between reviews are iterative, which allows another pass at incomplete or sub-par work. There are many Milestone Reviews used in Tiv-Model, summarised in Table 5-1 below.

Stage	Reviews	Purpose
Investigative	Mission Concept Review	Evaluate the mission concept and ensure it is accurate and feasible
Legislative	System Requirements Review	Determine if all requirements are captured and appropriately realised
	System Definition Review	Evaluate the conceptual definition of the mission solution and its suitability to the mission
	Mission Definition Review	Evaluate the conceptual definition of the mission solution, including human flight factors such as safety
Qualitative	Preliminary Design Review	Evaluate the progress and rigidity of the initial design
Quantitative	Critical Design Review	Check if the current design is fully realised and ready for production/integration
	System Integration Review	Ensure all design and procedural documentation is in place for integration
Amalgamative	Production Readiness Review	Check if design is in state for manufacture and assembly
	Test Readiness Review	Determine if system is commissioned and ready for acceptance testing
	System Acceptance Review	Determine if acceptance test was sufficient to satisfy customer
	Flight Readiness Review	Evaluate system readiness for launch
Operative	Disposal Readiness Review	Determine if decommissioning plan is suitable for project

Table 5-1 - Milestone Reviews

Milestones Reviews gather information into one place and provide an opportunity for consensus and feedback. When a Milestone Review is passed, the previous work can be considered “verified” for the purposes of project progression. This checkpoint system acts as a baseline for system confidence.

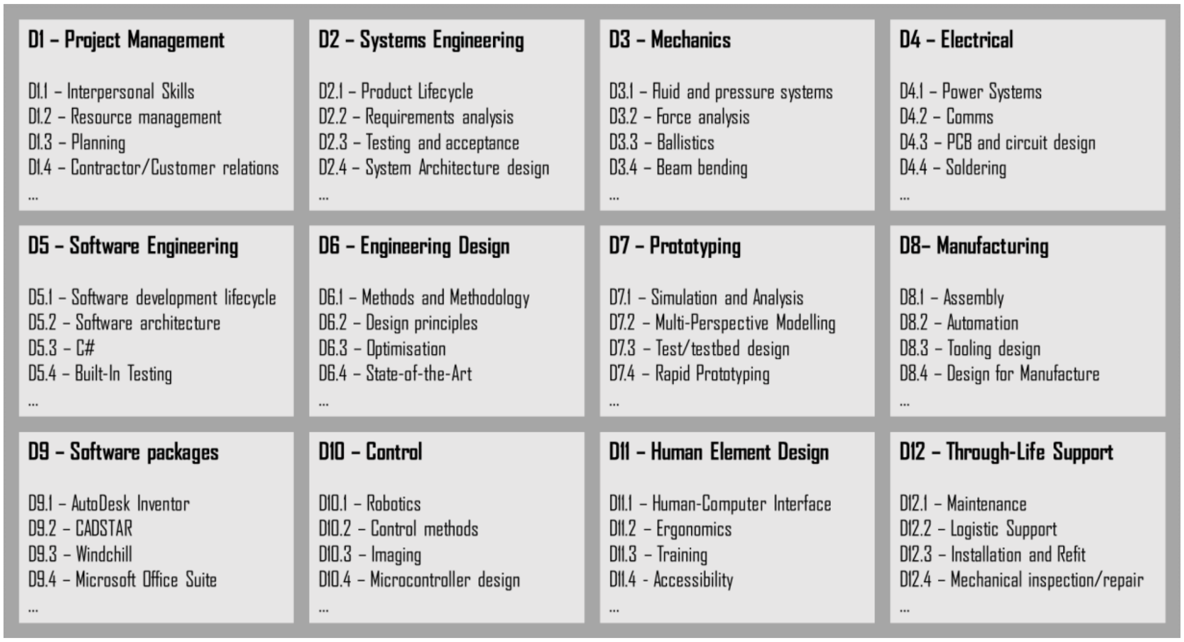
Knowledge Database

The Knowledge Database is list of categories of disciplinary knowledge, known as Domains. The Knowledge Database collects all Domains that are relevant to the organisation and some Domains will be used in every organisation project, such as Project Management. Other might be specialised, such as Orbital Mechanics or Ion Propulsion, which would be included as a Doman

Subset. Each Domain is assigned a code or number, which is used to tag Tiv-Model elements (such as Activities or Deliverables) and personnel.

Domain tags assigned to Tiv-Model elements such as Activities or Deliverables identify that item as requiring that type of Domain knowledge to complete. This identifies tasks that require specialists and will form part of the project planning materials. Individuals can be grouped by their specialisations or competencies; this helps create a register of individuals within the organisation and their skills. This can be used to find project participants and effectively manage the expertise within the organisation. Using both tagging methods together allows an organisation to distribute its staff according to project needs and personnel skills, enabling automated forward loading calculation and the ability for the organisation to track its knowledge needs.

Figure 5-10 shows the Knowledge Database drafted for a hypothetical organisation, complete with code tags and sub domains. This example shows just one potential configuration of the Knowledge Database, organisations that utilise Tiv-Model will populate their own Knowledge Database.



D1 – Project Management

D1.1 – Interpersonal Skills
D1.2 – Resource management
D1.3 – Planning
D1.4 – Contractor/Customer relations
...

D2 – Systems Engineering

D2.1 – Product Lifecycle
D2.2 – Requirements analysis
D2.3 – Testing and acceptance
D2.4 – System Architecture design
...

D3 – Mechanics

D3.1 – Fluid and pressure systems
D3.2 – Force analysis
D3.3 – Ballistics
D3.4 – Beam bending
...

D4 – Electrical

D4.1 – Power Systems
D4.2 – Comms
D4.3 – PCB and circuit design
D4.4 – Soldering
...

D5 – Software Engineering

D5.1 – Software development lifecycle
D5.2 – Software architecture
D5.3 – C#
D5.4 – Built-In Testing
...

D6 – Engineering Design

D6.1 – Methods and Methodology
D6.2 – Design principles
D6.3 – Optimisation
D6.4 – State-of-the-Art
...

D7 – Prototyping

D7.1 – Simulation and Analysis
D7.2 – Multi-Perspective Modelling
D7.3 – Test/testbed design
D7.4 – Rapid Prototyping
...

D8– Manufacturing

D8.1 – Assembly
D8.2 – Automation
D8.3 – Tooling design
D8.4 – Design for Manufacture
...

D9 – Software packages

D9.1 – AutoDesk Inventor
D9.2 – CADSTAR
D9.3 – Windchill
D9.4 – Microsoft Office Suite
...

D10 – Control

D10.1 – Robotics
D10.2 – Control methods
D10.3 – Imaging
D10.4 – Microcontroller design
...

D11 – Human Element Design

D11.1 – Human-Computer Interface
D11.2 – Ergonomics
D11.3 – Training
D11.4 – Accessibility
...

D12 – Through-Life Support

D12.1 – Maintenance
D12.2 – Logistic Support
D12.3 – Installation and Refit
D12.4 – Mechanical inspection/repair
...

Figure 5-10 - Knowledge Database example

A detailed visual representation of the Tiv-Model aspects working in together is shown in Figure 5-11.

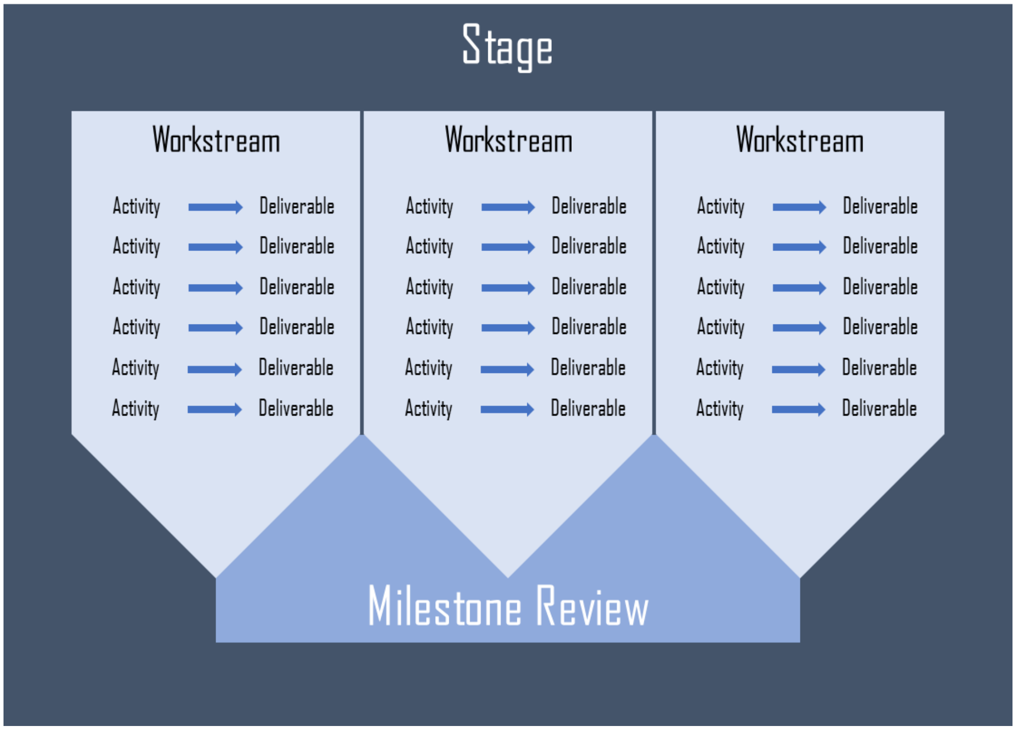
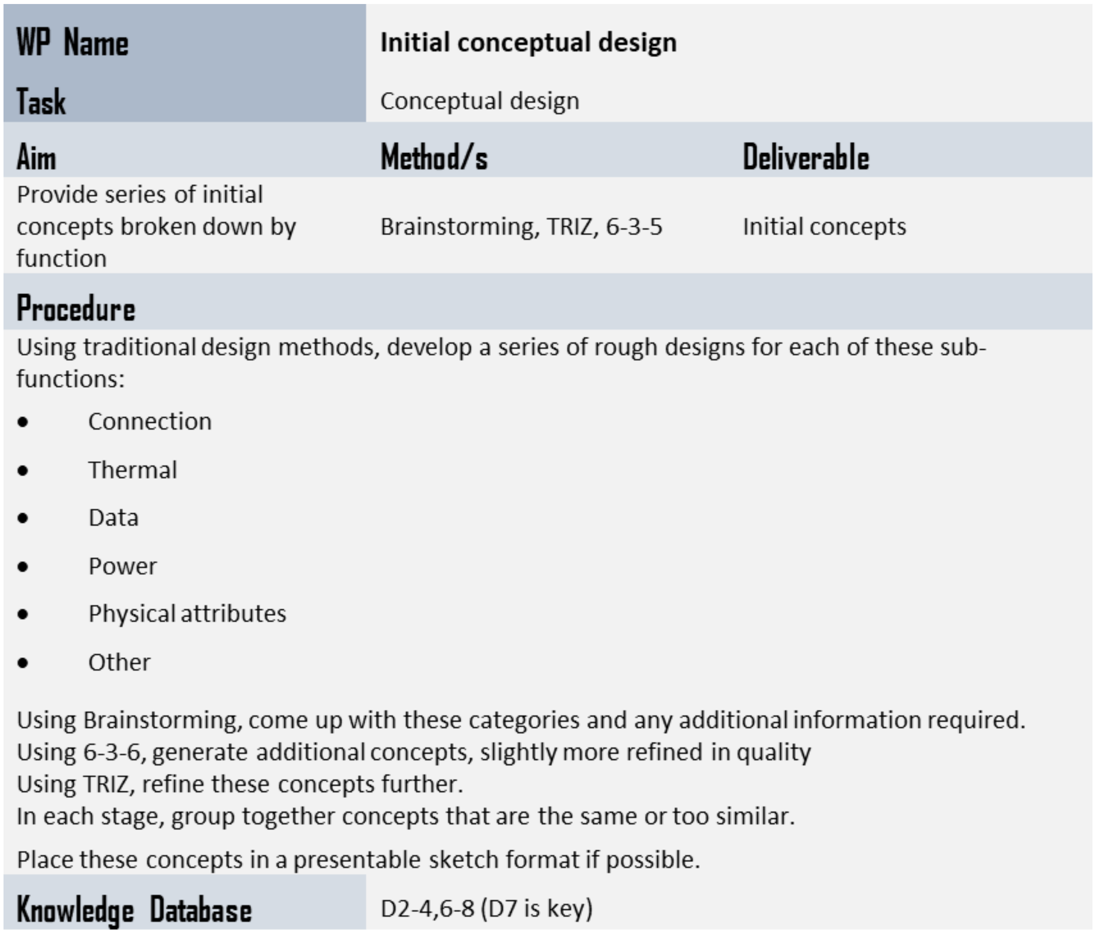


Figure 5-11 - Operational view of Tiv-Model elements

5.1.2 The Tiv-Model at the Mid-level

The mid-level of Tiv-Model is representative of the basic work package (WP) within a design project. This is used in most of the embodied work performed by teams and individuals. The graphical representation of the mid-level model is shown in Figure 5-12.



WP Name	**Initial conceptual design**
Task	Conceptual design

Aim	**Method/s**	**Deliverable**
Provide series of initial concepts broken down by function	Brainstorming, TRIZ, 6-3-5	Initial concepts

Procedure

Using traditional design methods, develop a series of rough designs for each of these sub-functions:

- Connection
- Thermal
- Data
- Power
- Physical attributes
- Other

Using Brainstorming, come up with these categories and any additional information required.
Using 6-3-6, generate additional concepts, slightly more refined in quality
Using TRIZ, refine these concepts further.
In each stage, group together concepts that are the same or too similar.

Place these concepts in a presentable sketch format if possible.

Knowledge Database	D2-4,6-8 (D7 is key)

Figure 5-12 - Tiv-Model work packages

Work packages

This diagram shows how work packages are delivered within the project as Activities tasks that output Deliverables. This work package management strategy is like solutions from research (Bundesrepublik Deutschland, 2004) where phases were broken down into tasks and activities, shown in Figure 5-13.

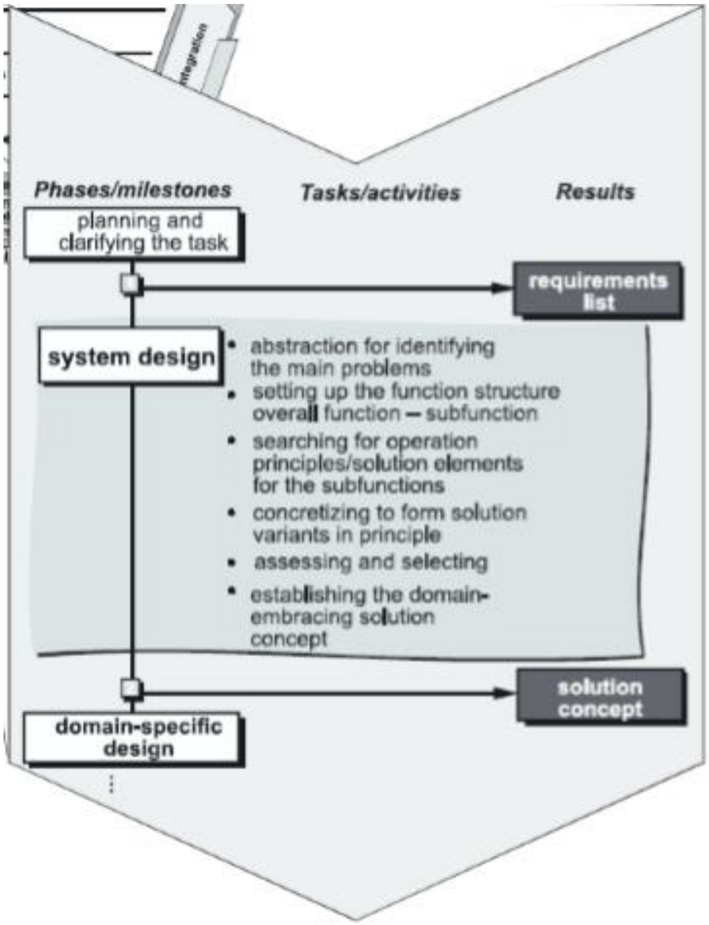


Figure 5-13 - V-Model's Process Modules

Work package management within the engineering lifecycle is a common practice, but rarely on that is defined by the methodology. Tiv-Model's work packages contain several elements: the WP task, code, procedure/method, Domain tags and deliverables.

WP task and code

Work packages will contain the header information that identifies it, these two items are the work package title and the work package code. The WP title is the known name of the work package and is used to identify what kind of work happens within it. The WP code is used to link the WP to the WBS performed in the Legislative stage of the Tiv-Model. Identifying the WP with a code allows specific identification and references across the organisation and enables automation of work package management.

Procedure and methods

The WP procedure is an informative aspect of a WP that tells the user how to perform the task. The procedure may contain guidelines, or a step-by-step run-down. The nature of the contents is flexible and can be tailored to the organisation's cultural needs.

WP methods on the other hand are descriptive and exact in nature. WP methods are generally referencing to pre-existing guides and documents, either created as part of design research, or generated internally by the company. WP methods may have codes to refer to them, indicating the type of activity and the stage that it is carried out in. It is common practice in systems engineering to have codified methods that predate the project, as these standardise ways of working and reduce project complexity.

Using procedures and methods allows project managers and systems engineers to evaluate the length of time of work packages and stages based on the contents of the procedures. One of the other advantages of using this kind of process is that it allows the organisation or project to establish the design freedom it wishes to give its engineers.

If an organisation is process-light, then the engineering content will be flexible and subject to the decisions made by the engineers involved. Process-heavy WPs may take longer and get bogged down but will ultimately increase the project has over the design and maintain important standards when doing so.

The Tiv-Model encourages both approaches, the only stipulation is that the WP generate the intended deliverable.

Deliverables and Domain tags

The Deliverables in the Tiv-Model WP shows which deliverable is expected from it. Project managers and systems engineers may control the means of achieving the content if they desire design limitations, but ultimately the deliverable must be satisfied.

Domain tags are used to indicate the required knowledge for the WP. WP managers can search the organisational Knowledge Database for personnel that have the same domain tag as the task.

5.1.3 The Tiv-Model at Micro-level

The Tiv-Model's micro-level takes the form of an embedded problem-solving tool that targets engineering design related problems. A problem-solving algorithm called C-QuARK (Ahmed-Kristensen & Wallace, 2004) was used to help aid engineers with decision making. It was designed to assist novice engineers, as it has them mimic the strategies and thought patterns that experienced engineers would follow. C-QuARK works by prompting the user with self-reflective questions regarding strategy, which the user then adopts. By asking themselves the questions the user gives themselves open-ended suggestions for actions they can take to overcome the problem. Once a strategy has been applied, but the problem is not yet solved, the user moves to the next strategy and they cycle continues.

C-Quark strategies

C-QuARK has eight strategies, shown in Table 5-2 below.

Consider	issues	What issues are relevant? Which are most important?
Question	data	How accurate is this? How was this tested/obtained?
	pursuing	How much will we gain? How much will we lose?
Aware	Of reason	Why was this process used? How does this function?
	Of limitations	What should I be satisfied with? How complete is this task?
	Of trade-offs	What other issues does this affect? Does it affect any other systems?
Refer	To past designs	Which designs are similar? How was this issue resolved before?
Keep	Options open	What should be considered later? Does this option limit us?

Table 5-2 - C-QuARK

Strategy 1: Consider the issues

The user must ask themselves what the considerations are within the problem. This opens the users mind to the possibilities of unseen factors. This helps identify which of the issues is most relevant. The user can then weigh of importance of the considerations, and thus the actions they pursue. This strategy can also be used to eliminate potential concerns.

Strategy 2: Be aware of the reason

C-QuARK promotes awareness through three perspectives. The first on, called “Aware of reason” is to enlighten the user on the reasoning behind something. For example, the user should ask themselves for the reason behind a component’s behaviour, or why it is used. This check can reveal the driving elements and reasoning behind decisions made.

Strategy 3: Refer to past designs

Referencing past designs is a common engineering practice and can be useful in fields with Design-To-Order (DTO) development strategies, despite product differences. This is due to key element commonalities across products. Experienced engineers often use this strategy to benchmark design performance, or to recall information on mitigating previous faults.

Strategy 4: Question whether it is worth pursuing

The “questioning” strategies direct the user to employ scepticism when reflecting on their approach or decision. This strategy questions the viability of pursuing a course of action. The user should evaluate the current options to determine solutions that are not viable. This is done by weighing pros and cons and will lead the user to optimise their solutions.

Strategy 5: Question the data

The second “questioning” strategy encourages analysis of observations. The user is prompted to check all relevant data they were given, such as dimensions, loads, safety ratings, and so on. The user will reconsider the accuracy of these measurements or discover crucial missing pieces of information.

Strategy 6: Keep the options open

This strategy prompts the users to maintain an open mind, and not eliminate paths to a solution. Insight into the user's decision making is gained through this strategy, and the user is encouraged to maintain flexibility and seek compromise.

Strategy 7: Be aware of the trade-offs

The second awareness-based strategy in C-QuARK reminds user to evaluate trade-offs. This means investigation of the relative issues and relationships, understanding which decisions will influence the design, and how. Pro vs Con weighing may require guesswork but will enable a balanced solution that satisfies the key design priorities.

Strategy 8: Be aware of limitations

Limitations can come from several sources, such as confidence and completeness of information, budget, individual abilities, or design constraints. Being aware of the limits of the project enable the user to discard options that are outside of the solution scope or are too complex.

These are generalised questions and provide only a vague sense of progression, so the authors rearranged their work into a more memorable and understandable format, seen in Additional details.

Additional details

The C-QuARK model is covered in additional detail in section 3.1.2 and is shown in Figure 3-4.

Example C-Quark scenario

This section shows a hypothetical worked example using C-QuARK. In this scenario a post-operation inspection of a component reveals that its screws are loosening. The engineer employs C-QuARK to work their way through the design problem to find a solution, and they do so by selecting a starting point on the diagram. The engineer starts at the "Aware of reason" strategy, as this is the information they find most pertinent to understand at this time.

Step 1: Aware of reason

The engineer lists as many reasons as they can think regarding why the screws are loosening and performs some inspection and investigation. They find the vibration of the housing causes the loosening. The engineer moves along the path to a new strategy; “Refer to past designs”.

Step 2: Refer to past designs

The engineer looks for solutions from previous designs under the same conditions. They find that, in the past, engineers replaced the screws with rivets. The engineer moves the next strategy on the diagram; “Consider the issues”.

Step 3: Consider the issues

The engineer considers what the main issues are with regards to the solutions and problem before them. Changing the design at this point would not be terribly costly, and the loosening will require constant maintenance. Maintenance was a key issue, and the engineer keeps this in mind as they move to the final strategy; “Aware of trade-offs”.

Step 4: Aware of trade-offs

The engineer weighs up their choices, they know that keeping the screws creates a maintenance problem, but also provides component access if replacements were ever needed. Rivets, however, are cheap and will solve the issue at the cost of easy access. The engineer determines that the Mean Time Between Failures of the internal components is high enough that rivets would be suitable to seal the enclosure.

In Figure 5-14 the arrows indicate the direction that experienced designers take when moving through strategies, however this does not rule out the option of moving backwards.

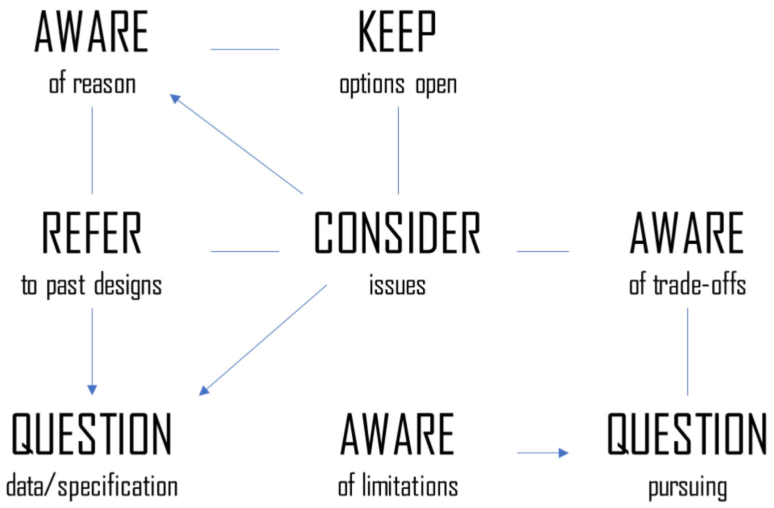


Figure 5-14 - C-QuARK shorthand

C-QuARK was adopted as the micro-level of Tiv-Model for several reasons. Engineers sometimes need low-level task related support to help with their design problems. This requirement is emergent in the field and is demonstrated in V-Modell XT, which includes its own problem-solving tool, shown in Figure 5-15.

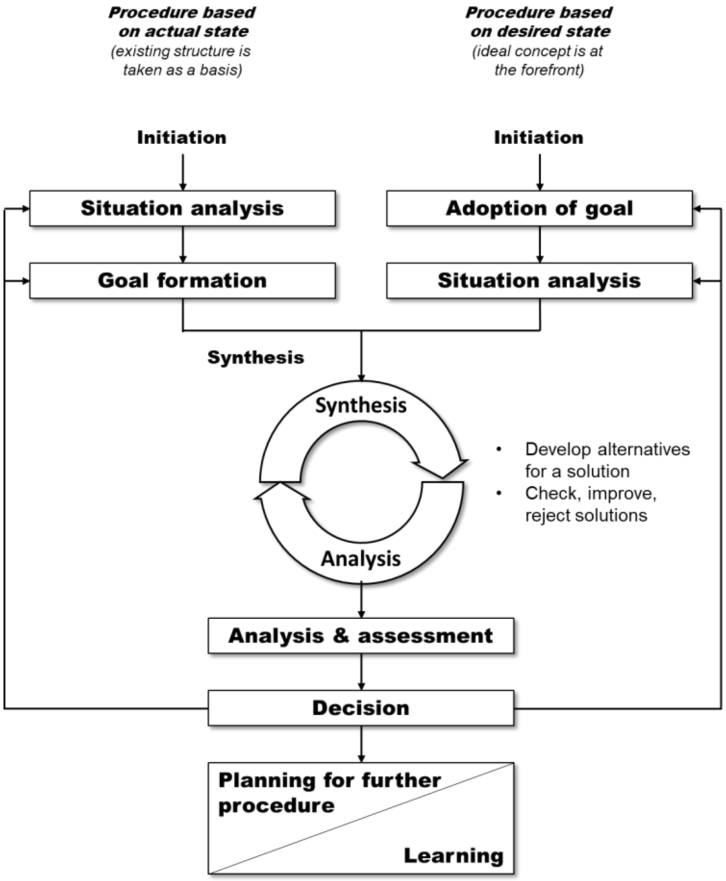


Figure 5-15 - V-Modell XT's problem-solving schema (Bundesrepublik Deutschland, 2004)

This problem-solving strategy was generalised and was a viable choice for applying to any kind of problem context. Unfortunately, its learnability was sacrificed due to the vagueness of the prompts. Another advantage of C-QuARK is that it has academic research to validate its performance, thus is was selected for use in the Tiv-Model.

5.2 Novel aspects and beneficial properties

In this section the novel aspects of Tiv-Model are discussed, highlighting the benefits that they can bring to CSE.

5.2.1 Academic basis – Industrial application

As shown throughout this thesis, the background of the Tiv-Model is rooted in design research. The fabrication and design of the Tiv-Model uses academic sources such as textbooks and papers to identify the current understanding and best-practice for methodology design.

Use of models

The Tiv-Model's macro, mid and micro levels are based on findings presented in academic publications and many of their features come from other models. The initial basis of the macro-level evolved from Yan and Zante's (Yan & Zante, 2010) Design Process Model, a development that can be witnessed clearly in earlier iterations of the model. The mid-level Work Package borrows layout elements from the V-Modell XT Process Module concept. The concepts borrowed were chosen based on their perceived usefulness. The micro-level of Tiv-Model is a fully independent problem-solving model on its own, C-QuARK. It was developed in an academic using engineers from industry within the research. This research rigidity demonstrates that Tiv-Model was developed with state-of-the-art considerations, lending credence to key publications in this nature and those who published them. the robustness of academic research is reinforced with papers such as these. Using C-QuARK and other academic materials satisfies the needs of academia, who require their models to be used and demonstrated.

Validation research

When designing the Tiv-Model, validation was considered from several perspectives. Firstly, how the Tiv-Model tackles product validation, and secondly how it tackles its own validation. Where validation is concerned, the means to achieve validity boil down to "satisfaction of the customer". Thus, when approaching the design of the model, both the quantitative aspects of academic validity and the qualitative aspects of industry validity are adopted. Complying with the needs of the industry while maintaining academic credibility allows Tiv-Model to be a viable choice. This approach is embodied in the effort to maintain the model's learnability without sacrificing its depth by using industry standard terminology. The viability of this approach is based on academic research, where ease of use, low barrier to entry and teachability are major influences on success.

Breaching adoption barriers for academic models

One of the initial challenges presented in the background research was the underutilisation of academic models. Industry's response revealed that there were many reasons methods were overlooked. These ranged from the perceived effort needed to implement the model, to the lack of qualifying evidence of effectiveness. These industry needs are addressed in the model to improve the odds of adoption from the academic side of the argument.

Guide to better methodologies

The Tiv-Model shall serve as a guide for those who wish to develop their own models and methods for industry. The thesis was designed to be a learning experience to show where previous methods and models could have been improved and demonstrate principles for designing them. Each design decision in the thesis was justified and the challenges were noted where they were present. The goal of this was to assist academic development and industrial uptake in models by creating a comprehensive reference material. The document also doubles as a teaching tool, and an example of deploying informative material is covered in Chapter 6. The core Tiv-Model premises was validated here and students engaged with the Tiv-Model in-depth. Teaching methodology in this manner helps generate a model-conscious engineering workforce that understand the benefits of an effective design methodology.

5.2.2 Modular structure

Some of the structural elements of the Tiv-Model are modular, meaning they can be removed or added to the desired effect of the project. The modularity serves to support systems involved in manned missions, or systems that are produced in number. Examples of modifications to Tiv-Model's structure can be found in Figure 5-16. This shows the hatched texture elements that are modular. The Investigative stage is modular and can be removed when Tiv-Model is deployed on projects with known legacy solutions or for missions where the solution concept has high Technology Readiness. The modular reviews in the Amalgamative stage are for projects with more than one system. Adjustments like this do not violate the information required in the Milestones or Deliverables and thus maintain the flow of logic.

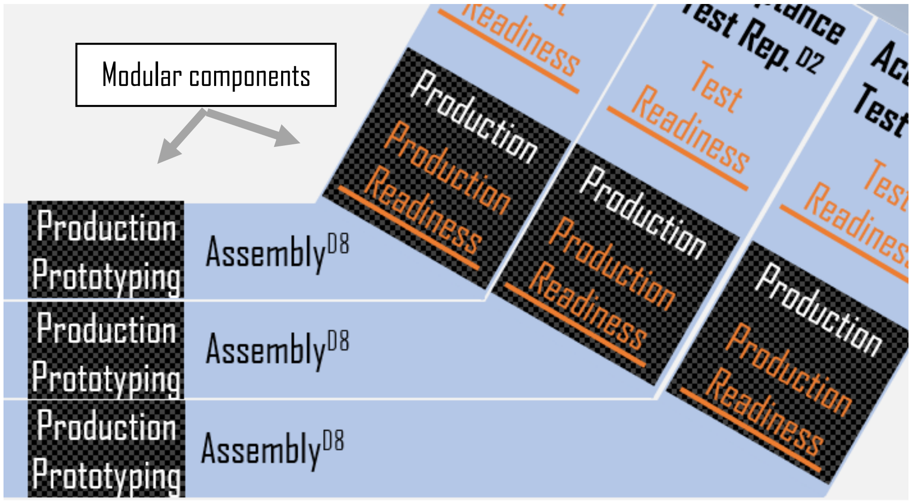


Figure 5-16 – Some modular elements ton Tiv-Model macro-level

Organisational compatibility

Tiv-Model is tolerant to superficial changes regarding the way that deliverables are achieved, due to the “objective-driven” nature of the model. This means that changes to methods, techniques and tools are acceptable. Allowing the use of organisational procedures prevents the Tiv-Model being implemented against the grain of the company culture. (Elsmore, 2001) Companies will not have to change their operating tools to incorporate the Tiv-Model, keeping the expenditure of effort regarding its adoption low. The choice of stage layout and common terminology also meld with current industry practice.

Model Flexibility

Engineers can see fit to choose their own method or path to executing the activity when using the Tiv-Model. This accommodates the resolution of unscripted situations and the chance that atypical methods can generate a better solution. Flexibility is also achieved in the digital tool, where data of any relevant form can be submitted as part of a work package. The final layer of flexibility is the model’s tolerance to deviation from the pre-planned path. Deviation from the plan can be accepted in mitigating circumstances due to the checkpoints in place. These checkpoints act as interfaces between two sections of the process where everything before that can be treated as one independent design activity. The Milestone Review can act as a grounding device, and if the project aims to get to that point, deviation is tolerated.

5.2.3 Internal validation

The validation of the Tiv-Model is critical to its novelty. As discussed in section 2.4.4, industry cites a lack of validation evidence as reasons for overlooking academic models. To combat this, the Tiv-Model adopts a validation strategy to demonstrate evidence of its viability.

Validation Square

The Validation Square is the centrepiece of the Tiv-Model's verification and validation plan, containing the means to provide theoretical and practical validity measurements. V-Square provides an opportunity to utilise academic models to bolster product quality and serves as a tool to standardise methodological validation. One function of this thesis was to present what the methodology validation process may look like to encourage others. Exposing the method to academia this way also doubles as a peer review.

Documentable validity

Ensuring the visibility of information is critical to validation. Those who are tasked with implementation of the Tiv-Model into an organisation will need to take this information to assist them. Academics who wish to scrutinise or utilise these documented validation practices can have to have a document source for information. Extra steps have been taken to justify the decisions and developments of Tiv-Model in this thesis. Documentation within the engineering lifecycle is also key and Tiv-Model deals with this in a similar way. All decisions and justifications are requested as deliverables in writing. This ensure there is evidence and justification for design decisions that can be referenced later in the project or audited.

5.2.4 Designer-centric development

Tiv-Model was designed from the ground with “designer-centrism” as one of the core tenets. The model has a series of features specifically chosen to help the engineer make decisions, stay flexible and keep informed. Novice engineers’ needs are accommodated, allowing organisations to reduce the risk of hiring them while freeing up experienced engineer time.

Learnability focus

The first piece of designer-centrism within the Tiv-Model is the focus on learnability. Novel ideas were used from social science research to improve learnability. Ideas involving visual information representation, phonetic memory techniques, and simplification of low-level responsibilities formed the outcomes of that research. Future plans for the Tiv-Model and this thesis involve generating a comprehensive manual. The creation of accessible manuals and reference materials is critical to learnability. Learnability is an important factor in adoption decisions as it directly correlates to the amount of effort organisations expend on implementation through staff training.

Novice engineer focus

Novice engineers are an important demographic within the aerospace engineering workforce, many efforts are being made by organisations to assist their development. Techniques used in the development of Tiv-Model aim to allow novice engineers to work with reduced uncertainty. This is accomplished through several methods, the first is C-QuARK. C-QuARK is a problem-solving method designed for novice aerospace engineers. It promotes a train of thought more emulative of experienced engineers. For this reason, it is incorporated as the micro-level problem solving schema in Tiv-Model. Novice engineers are also supported through the project planning process, as planners can clearly define procedures or work instructions for every. Planners can give as little or as much information about the activity as required, providing the novice a solid path to follow. This information can be accessed by anyone involved in the activity and is thus transparent. Learnability is improved through the removal of jargon and other high-requirement knowledge.

5.2.5 Goal Oriented design

The Tiv-Model’s Mid-level representation sets up a Work Package Management system, where engineers output activity information as a deliverable. The core requirement is the deliverable, and the method is flexible. This means that the engineering lead, or the task manager can choose whichever means are relevant to accomplish the activity. This has been referenced already throughout this section but is important to classify as its own novel aspect of Tiv-Model.

Designer freedom

The goal-oriented nature of the Tiv-Model gives the engineers many options. For more experienced engineers, the path of action laid out by the project management team can sometimes limit them in counterproductive ways. The experienced engineer's input with regards to flexibility is valuable, as the research shows that they benefit from being able to choose. Tiv-Model offers both freedom and optional constraint from the inclusion of work package management procedures.

Planner control

Using Tiv-Model the project manager and engineering lead has control over activities, procedures, and methods, and controlling these aspects at varying degrees will compliment certain project strategies. For example, enforcing a specific method to maintain a particular standard is one beneficial use of that control. It is up to the engineering leaders to implement high-level strategies, and Tiv-Model is a means of doing so. Novice engineers benefit greatly from this practice, as their instructions can be explicitly defined. Project leaders can also entrust their design teams with full or partial control over their activities. This benefits experienced engineers who are aware of team limitations, and will allow for optimisations to be made to the activity. Understanding when to exert or relinquish this control produces the best engineering results.

5.2.6 Multi-perspective design approach

Tiv-Model aims to improve design quality and reliability by instilling a multi-perspective approaches to information. A multi-perspective approach is a means of evaluating the amalgamation of all available information. The purpose of this is to perform an accurate evaluation of the situation looking at variables separately does not account for the complex relationships between them. An example of this process is multi-perspective modelling.

Multi-perspective modelling

The Tiv-Model's Quantitative stage calls for the use of Multi-perspective modelling, a term used to describe the creation of amalgamated analytical models that emulate aspects from multiple engineering discipline and the effects of the environment on the design. Generally, the analytical teams create several CAD models for thermal, mechanical, electrical, and other load types on a spacecraft. Independent analyses on these models will provide a result that does not include the compounding effect that each of the load types has on the other. A combinatorial explosion of complexity can occur when these aspects interact, especially in extreme environments like space. A single model that considers the combined effect of these conditions can generate a much more accurate simulation. This increases effort and complexity of the design task, but provides a more robust design, especially considering the lack of physical prototyping options for complex systems.

Non-destructive testing

Prototyping and physical testing is difficult for complex systems, as correct environmental conditions cannot easily be recreated and the fabrication of units for destructive testing is costly. Fabrication of test units is still viable, and can catch issues in a broader scope, such as in manufacturing and assembly. Simulations provide a range of data at an affordable cost and quicker pace. The challenges with simulation come with the skill, knowledge, and software requirements, as well as ar lack of “reality-checking”. Another drawback of simulation is that it is only as accurate as the person creating it. The risk can be partially mitigated with basic error checking through procedural application, but simulation results are still subject to other anomalous quality issues. The move to multi-perspective modelling requires a dedicated skill pool, a specialist set of software and a rigorous approach to quality assurance. However, the results are a compromise between robustness of design and time/cost in complex projects.

Concurrency incentivisation

The principles behind multi-perspective modelling approaches are the same as those embedded within concurrent engineering, which is the idea that quality is improved with continuous, real-time cooperation and input into one shared concept. Multi-perspective modelling requires at least a temporary bout of concurrent engineering to be accomplished and is a high information-flow activity. Tiv-Model’s multi-perspective approach has a distinct set of benefits that come with it but require these users to adopt concurrent processes to return the design robustness. In this way, Tiv-Model incentivises concurrent engineering practices to be used with the model, despite being compatible with non-concurrent approaches as well.

5.2.7 PLM integration

The Tiv-Model is also designed alongside a web app that helps manage the model. This piece of the work was not completed at the same rate as the research as it was not considered part of the contribution for the thesis. The web app was not coded by the author and thus cannot be considered a knowledge contribution. A proof-of-concept variant of this management app was developed, present on the university intranet. Even without an accompanying app, Tiv-Model allows for engineering system and PLM integration.

Knowledge database and resource allocation

The Knowledge Database is a powerful tool for the project, tags can attribute information to a activity, deliverable or team member. Tagging the activity allows the planner to mark the relevant knowledge requirements to that activity. This allows the project leaders to assign personnel to the task who are best qualified, and this decision can be made swiftly. Suitable alternative staff can also be requisitioned, or if that skill set is missing in the company, contracted for work. Project teams can also predict their forward load more accurately using this process. The web app also sorts based on tag, to allow rapid information acquisition and grouping.

Planning assistance and transparency

Tiv-Model planning activities are transparent, which makes the information flow accessible. When Tiv-Model is setup correctly, every participating member in the project can see the macro and mid-levels as the project front end. Engineers will see their planned work packages, deliverables, workloads, and objectives, and can view the same for others. Digital tools incorporating the Tiv-Model will also help display the information. Transparency is important as it aids communication between groups, which is especially important in a concurrent engineering environment. It also improves engineer’s awareness of the activities others are undertaking, to provide context to the bigger picture and drive prioritisation of tasks.

PLM system compatibility

Tiv-Model is like a traditional Product Lifecycle Management system in many ways, it’ embodies the product from conception to disposal. The web app provides a means for project planning and file management on a centralised network. Deliverables are submitted via an interface that links them to the work package activity, documents can be configuration managed. If a document is checked out, it cannot be edited by others. The file can be checked back in on completion and is then updated. Outside of the web app, the Tiv-Model is functional in existing PLM software, as its macro-model take a typical linear form.

Computer program

The Tiv-Model gains functionality from the webapp, which is unfortunately not novel enough to be considered a knowledge contribution. However, this is not required for Tiv-Model to function. The novelty of the webapp is due to its optimisation with Tiv-Model. It requires very little setup to produce a project plan following a Tiv-Model template, which comes with pre-written work packages. This speeds up the setup and allows quick editing to suit the project. The web app is a free, intranet-based package and thus can be accessed locally or outside of an organisation without the need for dedicated software. Lastly, it designates server space and track file versioning, allowing it to call files from the web app interface. These features are not novel themselves and are present in other PLM systems, novelty comes from Tiv-Model compatibility.

5.2.8 Potential benefits of Tiv-Model implementation

The Tiv-Model is designed as a quality improvement methodology, that sacrifices short term time and resource costs for long term gains via careful evaluation and quality control. Below shows the qualitative balance of benefits between these three factors.

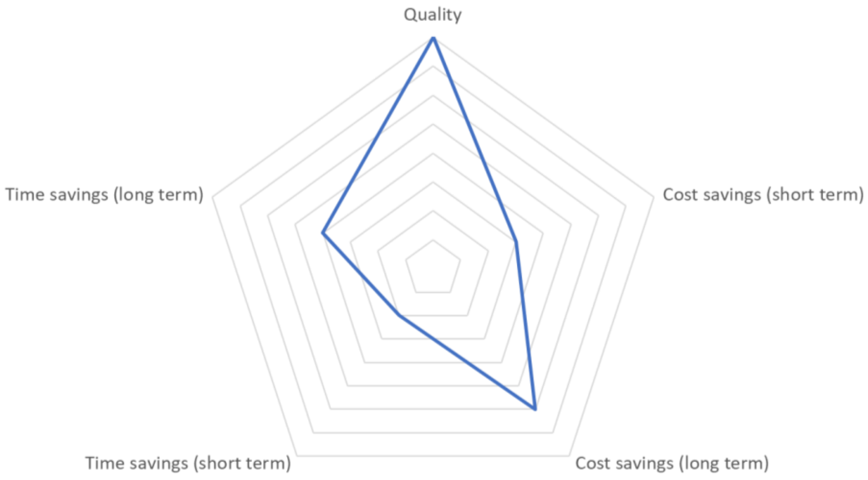


Figure 5-17 - Cost-Quality-Time focus of Tiv-Model

Overall, the potential benefits that Tiv-Model can bring to the design process can be summarised:

Engineer benefits

- Easy to use and understand current tasks.
- Information needed is provided at the time it is needed.
- Transparency in planning allows greater agency and communication.
- Novice engineers enabled to contribute more.
- Experienced engineers not relied upon too heavily, given freedom to design.
- Choice of method, tools and style dependant on designer or organisation.

Project benefits

- Computer aided validation focus has higher chance of ensuring correctness first time.
- Concurrent design options may help improve systems integration quality.
- Clear deliverables help improve error checking and identifying points of failure.
- Documentation of each stage is part of deliverables required, meaning retroactive checking and changes can be made during the project.
- More means for design validation.

Planning and Management benefits

- Stage and task breakdown is categorised to ease timescale planning and rough resource allocation.
- Sequential tasks broke down by discipline, allowing for either a traditional or concurrent engineering approach.
- Knowledge requirements for each stage are outlined, allowing plans for specialist help.
- Planning is transparent and thus easily communicable.

Organisational benefits

- Flexible goal-oriented design means tools and methods need not change.
- Keeping tools and methods means very quick and easy implementation into organisation.
- Reduce costs by;
  - Supporting inexperienced engineers
  - Using computer aided design validation as opposed to prototypes.
  - Retaining in-house tools and methods.

Industry benefits

- Methodology validation breaks down industry barriers for academic model acceptance.
- Steppingstone example for new, improved design methodologies.
- Hiring of inexperienced engineers will be justifiable, as risk is reduced.
- Non-destructive and computer aided means of design validation could reduce project costs across all projects.

The Tiv-Model was designed to provide mitigative properties that deal with challenges in complex systems. By assisting engineers with tasks, products with quality, organisations with efficiency and industry with standards, a series of actions take place to address the core problem.

To validate these claims, the next section addresses how Tiv-Model provides these beneficial aspects and adheres to the specifications generated in the previous chapter.

5.3 Adherence to specification

In this section, justifications are made for design decisions surrounding the Tiv-Model by referencing each feature to the specifications developed in Chapter 4, explaining why each feature is required and how it was represented the methodology. This is done to show that the methodology design process is verifiable. The method of requirements satisfaction is summarised in Table 5-3 below and detailed in the following sections.

Req	Means of Satisfaction
R1.1.1	Designed from requirements, validated against them using V-Square
R1.1.2	Multiple studies performed, Tiv-Model changes due to feedback from each step
R1.1.3	Follows the engineering design process, validates end product against requirements
R1.2.1	Sub-assembly, production, ETU and system testing, requires multi-perspective model
R1.2.2	Requires multi-perspective model deliverable
R1.2.3	Iterative evaluation during Qualitative and Quantitative stages
R1.2.4	Sub-assembly, production, ETU and system testing, requires multi-perspective model
R1.2.5	Requires multi-perspective model deliverable
R2.1.1	Requirements for engineering design methodologies, thesis design process in Chapter 2 and Chapter 3
R2.1.2	Requirements for engineering design methodologies, Chapter 4
R2.1.3	User feedback given via comparative and focus group studies
R3.1.1	V-Square, Chapter 6, Chapter 7
R3.1.2	Challenges of CSI and space systems, Chapter 2, aerospace common terminology, NASA/AIAA process
R3.1.3	Requires multi-perspective model deliverable, based on 3-column model
R4.1.1	Evaluated against V-Model in Chapter 6
R4.2.1	Mentioned in model educational material, thesis Chapter 5
R4.2.2	Mentioned in model educational material, feedback survey outcome, thesis Chapter 6
R4.2.3	Mentioned in model educational material, thesis Chapter 5
R4.2.4	Mentioned in model educational material, thesis Chapter 5
R5.1.1	Follows the engineering design process
R5.2.1	V-Square, Chapter 6, Chapter 7
R5.2.2	Requirements for engineering design methodologies, Chapter 4
R5.2.3	Academic roots and background research, Chapter 2, Chapter 3
R5.2.4	Multiple studies performed, Tiv-Model changes due to feedback from each step
R6.1.1	Rigid stage structure, Review Milestones act as anchors
R6.1.2	Rigid stage structure, Review Milestones act as anchors, foundation of requirements
R6.2.1	V-Square steps 3 and 4, Chapter 6
R7.1.1	Follows the engineering design process, validates end product against requirements
R7.1.2	V-Square step 5, Chapter 6
R8.1.1	Mentioned in model educational material, thesis Chapter 5
R8.1.2	Mentioned in model educational material, thesis Chapter 5
R8.2.1	Documentation as deliverable items, Milestone Reviews reports
R8.2.2	Documentation as deliverable items, archiving and decommissioning steps
R9.1.1	Principles of conduct, standard terminology, modularity, objective-based activities
R9.2.1	Rigid stage structure, principles of conduct, standard terminology
R9.3.1	Rigid stage structure, principles of conduct, standard terminology
R10.1.1	Web app, objective-based activities, CAD compatible format
R10.1.2	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R10.1.3	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R10.1.4	C-QuARK, mentioned in model educational material, thesis Chapter 5, Chapter 6

Req	Means of Satisfaction
R10.1.5	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R10.1.6	Macro, mid and micro level, C-QuARK, WPM, Tiv-Model, Methodology house
R10.2.1	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R10.2.2	Educational material, thesis Chapter 5, Chapter 6
R11.1.1	Educational material, adaptable to org, methods, high level, existing lifecycle knowledge and architecture
R11.1.2	Web app, lifecycle model, time scale, objective-based activities, Milestone Reviews
R11.2.1	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R12.1.1	Knowledge database, macro-level, Legislative stage, WPM tasks
R12.1.2	Knowledge database, macro-level, Legislative stage, WPM tasks
R12.2.1	Knowledge database, Milestone Reviews (MCR, SDR, PDR) multi-perspective modelling, Legislative stage
R12.3.1	Knowledge database, web app, PLM system adaptability, deliverables
R12.3.2	Knowledge database, Quantitative and Amalgamative stages, Multi-perspective model, Systems Engineers
R12.3.3	Knowledge database, macro-level
R13.1.1	Follows the engineering design process, validates end product against requirements
R13.1.2	Web app, objective-based activities, CAD compatible format
R13.1.3	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R13.1.4	Follows the engineering design process, Deliverables, WPM, Milestone Reviews
R13.2.1	Macro-level, Review Milestones
R14.1.1	Mentioned in model educational material, thesis Chapter 5, Chapter 6, Tiv-principles
R14.1.2	Mentioned in model educational material, thesis Chapter 5, Chapter 6
R14.1.3	Macro-level, micro-level, web app, Knowledge Database
R14.1.4	Macro-level
R14.1.5	Mentioned in model educational material, thesis, Chapter 3, Chapter 5, Chapter 6
R15.1.1	WPM, C-QuARK, Deliverables, activities, stages
R15.1.2	Review Milestones, stages, verification and validation, requirements
R15.2.1	Web app, lifecycle model, time scale, objective-based activities, Milestone Reviews
R15.2.2	Web app, lifecycle model, time scale, objective-based activities, Milestone Reviews, Knowledge Database
R16.1.1	Mentioned in model educational material, thesis, Chapter 3
R16.1.2	Activities, Deliverables, design process, Qualitative stage
R16.1.3	Stages, work streams, C-QuARK
R17.1.1	Macro-level
R17.1.2	Macro-level, mid-level, micro-level, workstreams, WPM, Review Milestones
R17.1.3	Deliverables
R17.2.1	Modular parts, Investigative stage, PRR, MDR
R18.1.1	Academic roots and background research, Chapter 2, Chapter 3, C-QuARK, Multi-perspective modelling
R18.2.1	Web app, objective-based activities, CAD compatible format
R18.2.2	Knowledge database, Quantitative and Amalgamative stages, Multi-perspective model, Systems Engineers
R18.2.3	Follows the engineering design process, aerospace design standards, Operative stage
R18.2.4	Aerospace design standards, standard aerospace technology, Milestone Reviews, workstreams
R19.1.1	Macro-model, objective-based activities, modularity
R19.1.2	Macro-model, objective-based activities, modularity, Milestone Reviews
R19.1.3	Macro-model, objective-based activities, modularity, Milestone Reviews
R19.1.4	Macro-model, modularity, Milestone Reviews, Lessons learned

Table 5-3 - Tiv-Model requirements satisfaction

5.3.1 Validation (R1)

R1.1: Do things right

R1.1.1: The methodology shall be tested against a validation standard (MV2) and R2.1.3: The methodology shall evolve from use-case feedback (C10) (VS6)

Validity can be measured by customer satisfaction via the product. In this case the product is the Tiv-Model and its clients are academia and industry. By evaluating the product against the requirements, validity for the Tiv-Model was attained. Incidentally, the first requirement listed was that the methodology was tested against the requirements. The background research showed that there were no validation standards for design methods or methodologies, which left room for a candidate. The candidate proposed in this thesis is the V-Square, which is present within the literature. This validation process is shown in Chapter 6, which is dedicated to the Verification and Validation of the Tiv-Model. The process includes a study that validates Tiv-Model via user input.

R1.1.2: The methodology shall undergo iterative evaluation (MR6)

Iteration within the design process is a recognised continuous improvement method, where quality and robust design is the primary goal. For this reason, there are iterative workstreams, indicated with an “i”, to that show where cyclical improvements can be made. Review Milestones are included in Tiv-Model to serve as validation checkpoints and to tie the model in with traditional complex system design using standard process items. They act as gates between stages to verify the work done to that point, work done between gates can be considered iterative.

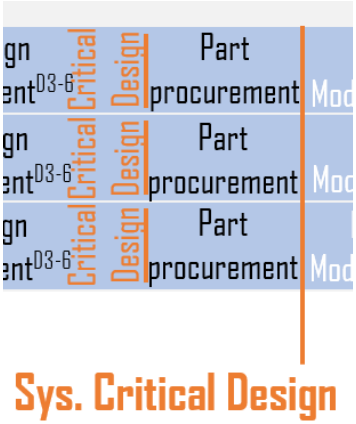


Figure 5-18 - Review milestones in Tiv-Model

R1.1.3: The methodology shall satisfy end user requirements (R1)

It must be ensured that the methodology is something that will deliver the desired output. This requirement may seem obvious but was overlooked in the literature definitions of methodologies simply for being a very baseline assumption. Tiv-Model validates its ability to meet end user requirements firstly through its roots in traditional design processes. This is supplemented by adopting principles regarding product needs (validation against requirements), optimisations of methods (objective-based activities), and others (such as iterative quality sweeps). These principles are justified with peer-reviewed publications in Chapter 6.

R1.2: Testing

R1.2.1: The methodology shall accommodate non-destructive testing (CS4), R1.2.2: The methodology shall accommodate virtual prototyping (SS3) and R1.2.5: The methodology shall accommodate multi-perspective modelling (SS3)

Full or partial scale prototypes of complex systems are resource intensive, and potentially destructive, especially with space systems as the test environment is inaccessible. Therefore computer-based modelling and simulation is important to evaluate a design in a cost and time efficient manner. Tiv-Model's idea of robust evaluation comes from the V principle, which stands for "Validation via multi-perspective modelling". This principle specifies that multi-perspective modelling should supplement a physical testing, especially in the early stages of the design process. Virtual testing will enable quick, iterative tests to be carried out earlier in the process with very low cost. This multi-perspective approach is a means of evaluation earlier in the process, before production and integration testing, it does not replace a majority of the system tests, but rather shifts the burden of performing destructive testing unless absolutely required. As a result, quality and reliability become a continually evolving aspect of the design process that is considered earlier. Multi-perspective approach increases design confidence and test accuracy.

R1.2.3: The methodology shall accommodate iterative, early-stage component testing (SS2) (MR6)

Virtual prototyping helps with early-stage sub-assembly testing, physical testing on components happens before this stage. During component-level testing at the Qualitative stage, aspects such as function and fitting can be determined accurately without modelling and simulation. This form of physical prototyping happens early to components, pre-CDR, to determine part suitability.

R1.2.4: The methodology shall accommodate sub-assembly testing (SS1)

Sub-assembly testing is supplemented by virtual prototyping and multi-perspective modelling. Suitable sub-assembly tests vary according to the system and intended environment. The goal of sub-assembly testing can range from integration testing, structural testing or environmental testing. This is primarily for the benefit of ensuring that the electronics and software will function under intended conditions. When combined with multi-perspective modelling, sub-assembly testing is useful for determining the interaction of components, fitting, software, and electronics.

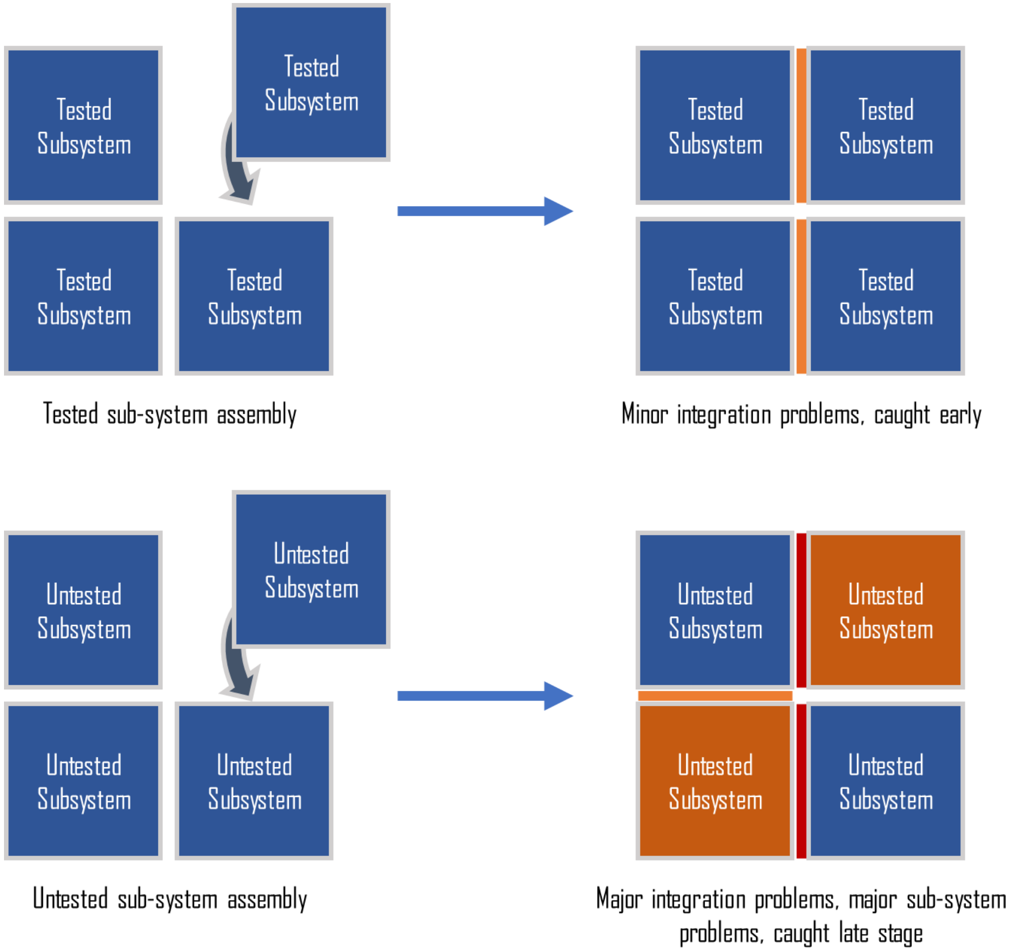


Figure 5-19 - Testing sub-assemblies before integration eliminates problems later in the project

5.3.2 Verification (R2)

R2.1: Do the right things

R2.1.1: The methodology shall be designed using a design process (MV1) (VS1) (R2)

As the literature defines, the Tiv-Model adheres to the design process, inspired by the 3-column model, and based on Cross' design model. This process embodies design engineering, which outputs a product based on the input need. This is followed through Tiv-Model, visible in the macro-level. Cross' model and the Tiv-Model stages are stacked up and compared in Table 5-4 below.

<table>
<tr><th>Cross' Model</th><th>Tiv-Model</th></tr>
<tr><td rowspan="2">Exploration</td><td>Investigative</td></tr>
<tr><td>Legislative</td></tr>
<tr><td rowspan="2">Generation</td><td>Qualitative</td></tr>
<tr><td rowspan="2">Quantitative</td></tr>
<tr><td rowspan="2">Evaluation</td></tr>
<tr><td rowspan="2">Amalgamative</td></tr>
<tr><td rowspan="2">Communication</td></tr>
<tr><td>Operative</td></tr>
</table>

Table 5-4 - Cross' model vs Tiv-Model

In complex systems design, the "communication" of the design implies delivery activities, including fabrication, testing, shipping, fitting, and operational duties.

R2.1.2: The methodology shall be designed from the requirements (MR8)

In any design project, the product should be based on the requirements derived from the need. Tiv-Model utilises the "Requirements for engineering design methodologies" document generated in this thesis as its reference material. Accuracy and fidelity of this documentation must always be maintained, and thus requires continuous improvement over the project lifecycle. Iterative improvements of this document should increase detail and specificities declared. Design confidence and robustness is bottlenecked at the requirements.

5.3.3 Innovativeness (R3)

R3.1: Unique Selling Points

R3.1.1: The methodology shall include and develop new validation standards (MV2) (R3)

This thesis explored design methodology evaluation and how a standard can be attained, with the intention of overcoming industry adoption barriers. One of the reasons that these barriers exist is that industry felt there was very little to model validation evidence. Thus, it follows that a validation standard should be developed to mitigate this issue. Established means of model evaluation are studied, and the Validation Square is selected. This 6-step method was used to validate the Tiv-Model using verification of the theory and practical behaviours of the model. This process is documented and advertised through Chapter 6 and Chapter 7.

R3.1.2: The methodology shall be developed in the context of complex space system design (MD2) (R3)

The Tiv-Model was designed with respect to the challenges found in complex systems engineering, as well as space systems, found in chapter 2 and 3. This evidence comes from the fact that the Tiv-Model was designed using the principles and design processes from aerospace engineering, centring on materials from NASA and AIAA. These contextual processes, and the challenges, were developed into requirements which serve as the basis for Tiv-Model.

R3.1.3: The methodology shall be developed to focus on multi-perspective modelling (SS3) (C9) (R3)

Tiv-Model adopts a multi-perspective approach, implemented by incentivising concurrency and information sharing in real time by using tools such as the web app, or other digital means. The basis of the Tiv-Model was also from 3-column model, which has multi-perspective modelling as its focal point.

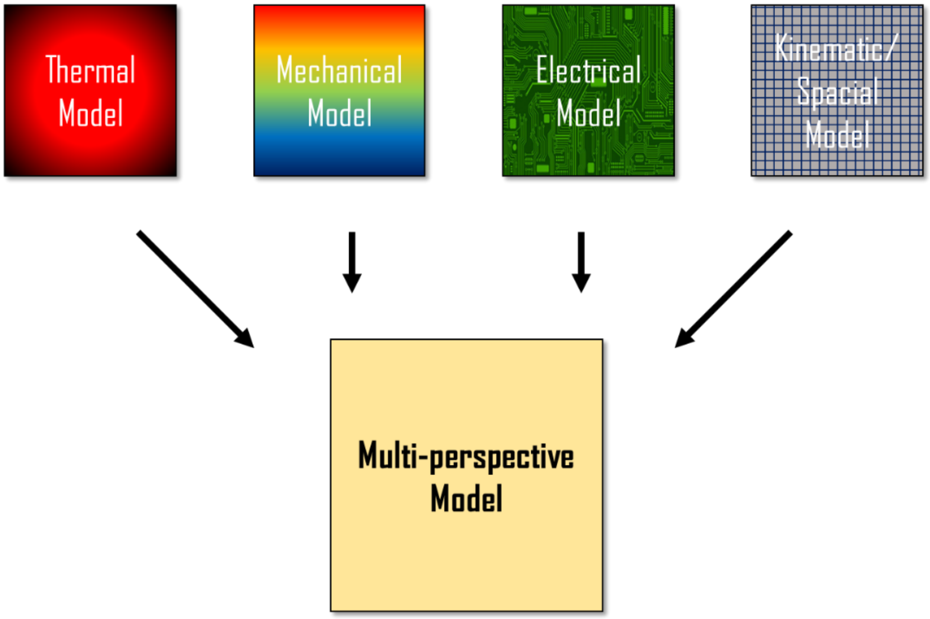


Figure 5-20 - Multi-perspective model components

5.3.4 Competitiveness (R4)

R4.1: Industry equivalency

R4.1.1: The methodology shall be evaluated by the relative performance against a benchmark (I2) (R4)

Validation of Tiv-Model against an accepted benchmark provides credibility to the arguments made in favour of its usefulness. The Tiv-Model is benchmarked against the V-Model, a widely used industry design model. This process is documented in Chapter 6.

R4.2: Adoptability

R4.2.1: The methodology shall explicitly state its potential impact (I2), R4.2.2: The methodology shall convey its efficiency and effectiveness for upper management (C6) and R4.2.3: The methodology shall convey the efforts in implementation for middle management (C6)

When pitching the model to concerned parties, communication of the benefits and drawbacks of the engineering methodology are essential. Pros and cons can be framed against a common benchmark (in this case, V-Model), and relative performance in various aspects can be measured.

This can be documented as communicative educational material. Organisational leaders will desire knowledge on a model's relative performance metrics. It is important to communicate these because they drive implementation. It is also important to state the kind of impact to be expected from this methodology and what kind of effort is required to implement it. This is useful information to those who must enforce the change, and to those who must use it. For these reasons, the methodology's educational material contains all these pieces of information. The results of the comparative study in Chapter 6 are a good source of relative performance metrics.

R4.2.4: The methodology shall convey its ease of use for engineers (C6) (C8)

End users are the ultimate decider of a model's viability, and their reluctance to accept the model is a resistance to change that must be mitigated within the model. Tiv-Model was designed to be easy to learn and use, and encourages learning using a positive reinforcement strategy. The research in this thesis is a good communicative tool to convey Tiv-Model's benefits, and this chapter is a useful tool to provide academic justifications. Features like C-QuARK and WPM provide useful tools for the end user. Transparency of information and visual learning aids also accompany the educational material to make it accessible to all.

5.3.5 Objectivity (R5)

R5.1: Systematic design

R5.1.1: The methodology shall follow a systematic design process (VS1) (R5)

The Tiv-Model follows the engineering design process laid out in Cross' model, shown in Chapter 3 and Chapter 5. This is a chronological process that is supplemented with iterative tasks.

R5.2: Scientific origins

R5.2.1: The methodology shall convey its validation procedure (I1) (R5)

The academic origins of the Tiv-Model are documented in this thesis through the chapters. The validation procedure used, the Validation Square, is identified in Chapter 3 and used as an example in Chapter 6 and Chapter 7.

R5.2.2: The methodology shall generate a Requirements document from literature (MV1) (R5) and R5.2.3: The methodology shall be grounded on state-of-the-art research (PB8) (MR1) (R5)

By treating the creation of an engineering design methodology in the same manner as an engineered project, the verification benefits of the process are retained. The Tiv-Model is based on the "Requirements for engineering design methodologies" document created in Chapter 4. The Tiv-Model is also based on state-of-the-art research. This research is identified and classified in Chapter 2, Chapter 3 and Chapter 4.

R5.2.4: The methodology shall evolve from heuristic feedback (C10)

Performing a task is the best way to learn it. This is one of the commandments of method design and is reflected in the testing requirements of the methodology. Chapter 6 and Chapter 7 detail the studies performed with Tiv-Model, both of which involved user feedback on the model's viability. These perceptions are delivered in post-use case surveys, providing the kind of detailed feedback required to adjust.

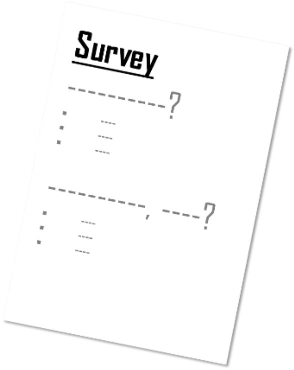


Figure 5-21 - Surveying participants generates feedback

5.3.6 Reliability (R6)

R6.1: Consistency in delivery

R6.1.1: The methodology shall operate similarly in each instance (VS2) (R6) and R6.1.2: The methodology shall deliver consistent results (VS2) (R6)

When Tiv-Model operates similarly across use cases, it ensures that expected performance criteria are met, and that product qualities are comparable. The Tiv-Model is tolerant of different organisations and use cases, reflected in its modularity and objective-driven activities. Consistency in outcome is enforced via the use of deliverables and through Milestone reviews, these check that the correct output has been generated. The rigidity of the Tiv-Model's macro-level stage-by-stage process also reinforces output consistency.

R6.2: Consistency in analysis

R6.2.1: The methodology shall work with design problems that are comparable (VS4)

The design problems relevant to the methodology's intended use were identified. The example problems were as complex systems engineering projects, particularly space systems. The Tiv-Model is to be used in large scale projects. These kinds of projects are not entirely reflected within the example problem in Chapter 6 (agricultural rover), but information from those projects were extrapolated in Chapter 7 using feedback from industry engineers. The example problems were suitable for several reasons; they shared many commonalities with large scale projects. There were team resource allocation needs, sub-assemblies, and various disciplinary teams coming together. These common factors enabled the results from the comparative case study to be extrapolated, using V-Square, to infer the likely performance of the model in an ideal scenario.

5.3.7 Validity (R7)

R7.1: Promises vs Delivery

R7.1.1: The methodology shall adopt requirements focused design (MD2) (MR8) (R7)

A requirement focused approach was incentivised in Tiv-Model, with a strong emphasis on an evolving requirements document being developed early on. These requirements are "reality checked" with the client in the meetings and reinforce them with milestone checkpoints at certain intervals throughout the project. The requirements are called upon throughout the project, and ultimate serve as the verification method used in the Amalgamative stage's acceptance tests, as all designs are evaluated against the original requirements.

R7.1.2: The methodology shall demonstrate that it is responsible for output delivery (VS5)

Chapter 6 demonstrates that the Tiv-Model's application results in the improvement of the design process relative to the V-Model. The studies were controlled by limiting the participants to the use of Tiv-Model or the control model. Participants were encouraged to discuss any alternative paths or alternative pieces of information they used outside of this, to determine when the Tiv-Model's influence is reduced or tainted. These findings were communicated via participant survey.

5.3.8 Comprehensibility (R8)

R8.1: A priori justification

R8.1.1: The methodology shall address its application as opposed to its knowledge (I6) and R8.1.2: The methodology shall provide a basic understanding of its decisions (R8)

From an industry perspective, engineers care most about the workability of their methods and what they can do for them, rather than how they came to be. When outlining the process for developing the Tiv-Model, this addresses the knowledge behind it and not the application. Instead, the main communicative documentation available is the training material. This document will have the description and functionality of the Tiv-Model, including how to use it, but without the theory of its inception. The justifications of each of the design decisions made with the model should be present, but not to the level of detail that tails back to the depths of the research.

R8.2: Posteriori justification

R8.2.1: The methodology shall accommodate design reporting and error checking (SS4) and R8.2.2: The methodology shall accommodate post-use documentation (C5)

The literature showed that a significant number of spacecraft failures may have been down to human error. The exact number is unknown, as are the specific causes. This kind of error is avoided through error checking and process review. The Tiv-Model supports documentation via the web app, or integration with a PLM system. The "deliverable" system employed by Tiv-Model ensures that key information is documented. Review Milestones also supply this function, enabling work reviews to happen intermittently through the design process. These are both ways to log and error check the design. Compiling a "lessons learned" set of documentation is also a valid tactic to ensure future failures are mitigated. Tiv-Model incorporates the writing of this documentation in the archiving activity, taking place at the end of the Operative stage. Using file linking with WPM tasks can help with document traceability.

5.3.9 Repeatability (R9)

R9.1: Adherence to methodology cross-instance

R9.1.1: The methodology shall be tolerant to slightly different circumstances (VS2)

The Tiv-Model is flexible and tolerant to a variety of circumstances around organisational behaviour. Organisational culture exists, and individuals have predispositions towards working in certain ways. Instead of fighting against this human component of design, Tiv-Model accommodates using flexibility of the method, tool, or path choice, so long as the deliverables and milestone requirements are satisfied. Modularity enables the Tiv-Model to be used in scenarios with personnel on-mission, where there is a production run, or even if there is a re-used legacy design.

R9.2: Comparability of tasks and R9.3: Comparability of outputs

R9.2.1: The methodology shall keep activities consistent in cross-instance application where possible (VS2) (R9) and R9.3.1: The methodology shall have its outputs remain consistent in cross-instance application where possible (VS2) (R9)

The flexibility of Tiv-Model at the high end is limited as the product of the methodology must be generated following a systematic model. With these limitations, activities at the stage level are enforced by disallowing flexibility. This, along with mandatory deliverables and Tiv-principles, maintains output consistency. Commonalities across industry, such as terminology and milestone review concepts help maintain cross-instance consistency.

5.3.10 Learnability (R10)

R10.1: Ease of learning

R10.1.1: The methodology shall support methods and tools (MD1) (C2) (C9)

The literature suggests that most design activities in current times are handled via computer tools, the author’s experience compounds that realisation. The personal computer is the most common engineering tool, being able to produce CAD, documentation, communication and so on. Tiv-Model can be developed in a way that supports the use of digital tools. This is accomplished allowing Tiv-Model to be integrated into a PLM system, or giving the option of using the Tiv-Model web app. Use in a PLM system will allow document tracking, and config management. Any method or tool that delivers the output required of an activity can be used with the Tiv-Model, due to its objective-based activity strategy.

R10.1.2: The methodology shall adopt a top-down approach to training (PB7), R10.1.3: The methodology shall adopt a practical teaching approach to methods (C7) (R10), R10.1.4: The methodology shall teach its low-level functionality (PB2) (C7) and R10.1.5: The methodology shall come with a manual (MR2) (R10)

The teaching experience for Tiv-Model is crucial to enable its implementation into an organisation. Learnability and teachability are part of the communication of design research, advances in this research have been used in teaching Tiv-Model. When being communicated to an organisation, the Tiv-Model is taught form the top-down. The drive for implementation should come from management and planning, thus it is imperative they have the knowledge for such a change. This is enabled through the educational reading material for the Tiv-Model. On top of existing materials, the Tiv-Model will also come with an operational manual. The Tiv-Model manual will make recommendations for methods and procedures to act as a default choice for each activity and deliverable. Phonetic tools (Tiv), visual diagrammatic aids and C-QuARK method are educational tools baked into Tiv. Reproducing this teaching material in its entirety is outside the scope of the thesis, but the training materials provided for the studies are suitable to demonstrate the information. The teaching plan for Tiv-Model within an organisation is shown in Figure 5-22.

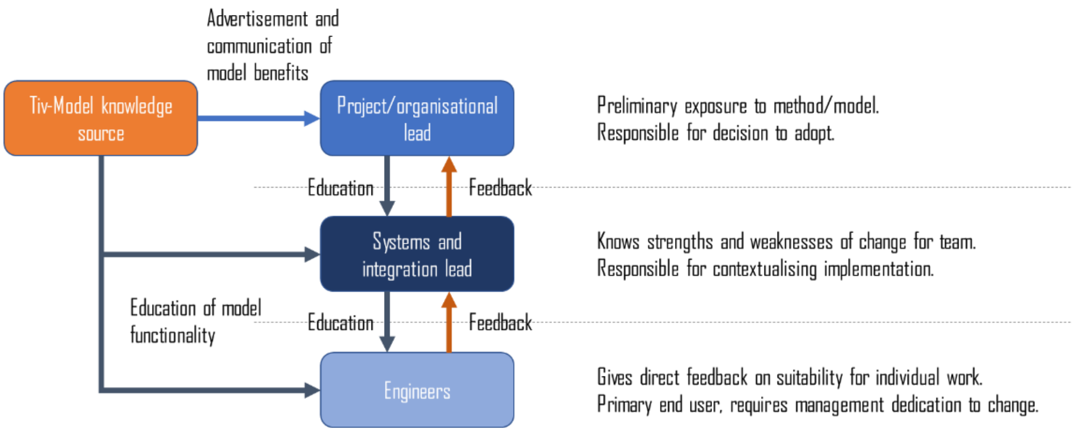


Figure 5-22 – Education-feedback loop for organisational change

R10.1.6: The methodology shall represent complex concepts with models (MR3) (C8)

Representing aspects of the Tiv-Model visually is quite effective at simplifying complex information. This is done by breaking down the Tiv-Model into three distinct scales, macro, mid and micro, each with their own representative model. These viewpoints are limited to partition the information for the user and prevent information overload. This also highlights the relevant information; a user will not need the macro or micro-levels when looking at the work packages. The commitment of the thesis to model based learning is reinforced in Chapter 8, in the summary.

R10.2: Willingness of learning

R10.2.1: The methodology shall adopt a positive reinforcement teaching strategy (C7)

As far as teaching goes, a strategy that students enjoy and benefit the most from is one where their learning is positively reinforced. Linking positivity and learning does well to aid human brains in retaining the information as well as desiring to learn more, learning feels rewarding and thus students wish to pursue it. A small amount of research concludes that, in an engineering design environment this concept can be introduced into learning by means of a practical approach, “do the methods” rather than “learn the methods”. Teaching of the Tiv-Model involves performing the actions taught in a workshop environment, this is reflected in Chapter 6.

R10.2.2: The methodology shall have shared materials to promote discussion (MR2) (R10)

The existence of the educational material and the discussions in Chapter 5, including the demonstration of the materials used through to Chapter 7 demonstrate them. Additionally, the Tiv-Model shall be accompanied by an operational manual for organisations to teach and implement.

5.3.11 Applicability (R11)

R11.1: Applicable to organisation and R11.2: Applicable to problem

R11.1.1: The methodology shall be quick and efficient to implement (I9) (R11), R11.1.2: The methodology shall support management tools (I10) (PB10) and R11.2.1: The methodology shall advertise its methods (I4)

Organisations value methodologies that are effective, efficient during require low effort to implement. Adopting a methodology comes with time and monetary costs, mapped to re-education and re-tooling. Implementation of an academic model is make or break when the effort is considered and Tiv-Model mitigates this in several ways. Tiv-Model has a low implementation cost, its flexibility means that tools do not have to be changed. The educational materials will include an implementation guide and include information on who needs what information. Transparency is also a method that reduces implementation effort, as all involved parties are aware of what needs to happen and when. This information is centralised in the educational material, alongside the information regarding methods and procedures.

5.3.12 Efficiency (R12)

R12.1: Resource efficiency and R12.2: Personnel efficiency

R12.1.1: The methodology shall accommodate resource allocation and planning (C4) (C8) and R12.2.1: The methodology shall accommodate personnel allocation and planning (C4) (C8)

Knowledge and resources are handled via Tiv-Model’s inclusion of Knowledge Databases. When personnel are tagged, they can be allocated to activities or deliverables with the same tag, ensuring that they are doing the work they are most suited for. This also works to measure and plan forward loading of personnel. Costs and other resource expenditure are planned during the Investigative and Legislative stages of the design process. Work Package Management in the mid-level also helps allocate resources to tasks, and the web app accommodates all these things.

R12.1.2: The methodology shall disincentivise excessive resource expenditure (R12)

Efficiency is maintained through use of academic models as well as adherence to the design process with no redundant processes. Efficiency is boosted through aspects of the model such as multi-perspective modelling, which makes prototyping more efficient, and the Knowledge Database and WPM structure, which makes planning more efficient.

R12.3: Effort expenditure

R12.3.1: The methodology shall accommodate data management tools (MD3) (C2)

The TIv-Model web app tracks files and relationships between them and tasks. Thus, engineers can quickly access files. Additionally, the compatibility of Tiv-Model with CAD practices and other PLM systems means that it can be implemented into existing infrastructure within an organisation.

There are no blockers on the kinds of data management activity that Tiv-Model can handle. The Knowledge Database is another example of data management that Tiv-Model engages in.

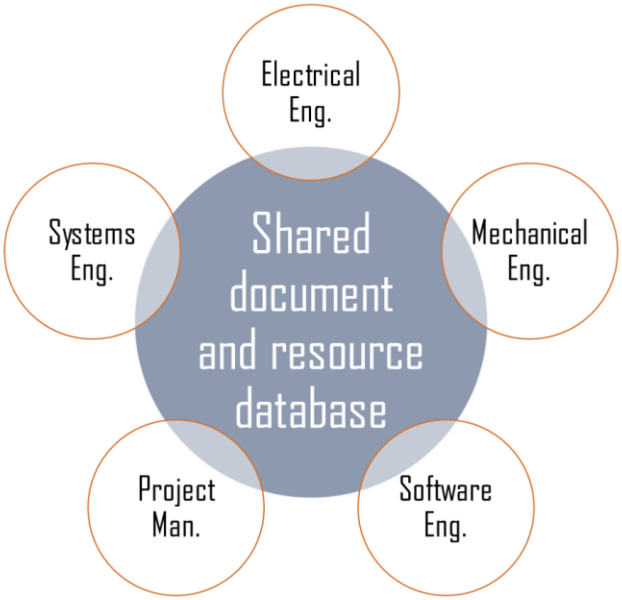


Figure 5-23 - Overall concept of a shared data management system

R12.3.2: The methodology shall accommodate concurrent engineering principles (PB9) (MR7)

To achieve effective and efficient design teams must operate together, and at times instantaneously. Multi-perspective modelling is but one key feature of Tiv-Model that requires a concurrent approach to design. This aspect, and concurrency itself, is accommodated in Tiv-Model using various techniques. The Knowledge Database is one means of enabling concurrency, as it assists in personnel load planning. The Amalgamative and Quantitative stages have tasks that require iterative concurrent work to be performed. The requirement within the model of the existence of Systems Engineers as interfaces also accommodates concurrent practices.

R12.3.3: The methodology shall map design resource flow (C1)

There are several aspects of the Tiv-Model that consider resource flow. Firstly, the flow of people resource is managed via Knowledge Databases and the deliverables system. Personnel can be assigned to tasks this way, and alternatives can be acquired if availability becomes a problem. The web app is the second means of resource flow consideration, managing the information in an automated manner. Finally, consideration of resources are planned early in the Tiv-Model, located in the Investigative and Legislative stages.

5.3.13 Effectivity (R13)

R13.1: Perceived effectiveness

R13.1.1: The methodology shall produce design solutions through its adherence (PB4) and R13.1.4: The methodology shall comprise of methods with measurable outputs (C5)

Tiv-Model follows the basic structure of a design methodology, based on the best academic understanding of design models. There are recommendations for methods, but never mandatory, instead the implementing organisation can “plug-in” their own procedures if they are suitable. Methods are further managed through Work packages, describing the procedure taken and the output required. These methods are validated through various Milestone reviews and acceptance tests to ensure the correct end-product is delivered.

R13.1.2: The methodology shall accommodate CAD (C2) (C9)

CAD is now industry standard practice, Tiv-Model accommodates this in the formulation of its deliverables. The deliverable itself will generally take the form of a digital file which will be managed by the web app or PLM system. All computer-generated files are compatible with the chosen system, and most of the design analysis in the Qualitative and Quantitative stages rely on computer analysis.

R13.1.3: The methodology shall recommend best-in-class methods by default (C3)

Tiv-Model is based on structuring that values flexibility for engineers, allowing them to choose their methods so long as they satisfy the deliverables. This is a preferred solution for organisation with a mix of engineers. Tiv-Model’s effectiveness comes from the recommendations for “best-in-class” methods. These viable choices are recommended based on the deliverable and presented in the educational material. Chapter 6 has a summary of some of these methods.

R13.2: End goal vs actuality

R13.2.1: The methodology shall contain iterative validation milestones (MR6) (R13)

Tiv-Model contains iterative validation milestones in several forms. Firstly, as Milestone reviews, punctuated between stages as a checkpoint. Secondly, as testing elements through the Qualitative, Quantitative and Amalgamative stages. Finally, as supplementary reviews and WPM tasks through the remaining design stages.

5.3.14 Problem Specificity (R14)

R14.1: Definition of scope

R14.1.1: The methodology shall differentiate between its design principles (I7)

The Tiv-Model, on top of the operational guidance, follows three main principles. “T” stands for “Target-based activities”, which calls on the engineers to derive their activities around the objective, rather than the procedure. “I” is for “Iterative design verification”, which states that evaluation is an iterative quality improvement process. “V” means “Validation via multi-perspective modelling”, which requires that the design be evaluated with an MPM. These distinguishable principles are clear on their demands of the user, and are mentioned in the educational material.

R14.1.2: The methodology shall provide representation of its methods (I5)

Complete and accurate representation is done by citing the literature origin and reference materials. This helps maintain accuracy and leaves little interpretation room within Tiv-Model, but also helps boost the utilisation of academic source material. Recommended methods are listed in Chapter 6 and presented within the educational material.

R14.1.3: The methodology shall provide representation of relevant non-design factors (C1) and

R14.1.4: The methodology shall provide a comprehensive overview of the design process (MR4)

Tiv-Model displays some considerations for the non-engineering aspects of the project. Organisational needs are considered via the training material, project needs are communicated via the Legislative stage and iterative management tasks through the design stages. The knowledge Database also maps the organisations knowledge needs to the staff’s capabilities. The macro-level model presents this combined view as the core of how the Tiv-Model operates.

R14.1.5: The methodology shall specify applicable design circumstances (R14) (VS3)

The intended problem space is the complex systems field, particularly space systems. This information is identified in Chapter 3 and clarified throughout the thesis, especially in Chapter 5 and Chapter 6.

5.3.15 Handling Complexity (R15)

R15.1: Task translation

R15.1.1: The methodology shall break tasks into simple objectives (C8) (R15)

Tiv-Model is a deliverable, objective driven process where the outcome is delivered regardless of the means. The main method of objective simplification lies in the deliverables and milestones structure. The methodology's approach to problem solving follows Wynn and Clarkson's idea of a procedural and stage-based methodology approach. This approach provides the method and methodological structure necessary to tackle complexity by maintaining the mid-level process. Uncertainty is also reduced with the introduction of scheme such as C-QuARK.

R15.1.2: The methodology shall impose useful limitations on design (CS3) (R15)

Limitation control, to an extent, is set by management via the imposition of methods and work packages. Limitations are also created via the nature of deliverables and milestones. Micro-level Tiv-Model contains a problem-solving schema for engineers that will help them make decisions. The requirements document is the main means of limitation in the design process, as this is the benchmark for validation of the design at the end of the process.

R15.2: Complex design management

R15.2.1: The methodology shall accommodate PLM systems (CS1) (MD1) (MD3) (C2) (C9) and R15.2.2: The methodology shall accommodate knowledge and data management tools (CS2) (MD1) (MD3) (C9)

PLM systems are at the heart of the complex systems engineering process and are thus accommodated by Tiv-Model in several ways. Tiv-Model is a product lifecycle model, and thus has the correct architecture for PLM systems. The Tiv-Model's web app acts as a rudimentary PLM system in situations where none is available. It, or the PLM system, can accommodate data and knowledge management and distribution of design tools via the network. Timescales and

Milestone reviews are also common elements in PLM systems, as well as deliverable items, which are also managed. Tiv-Model works on the same principles, and thus blends with the concept.

5.3.16 Problem Solving Cycle (R16)

R16.1: Schema

R16.1.1: The methodology shall communicate the designer's knowledge requirements (NE1) (R16)

The engineer's knowledge needs were a focus of the thesis research, identified in Chapter 2 and Chapter 3 while being embodied in Chapter 5. Literature defined needs of novice engineers are mitigated by the inclusion of C-QuARK. These are also brought up in the educational material for engineers to understand.

R16.1.2: The methodology shall adopt a problem-oriented approach (PB1)

The Tiv-Model's structure is built on a problem-oriented model of the design process, disincentivising solution-based ideation. This is embodied in the Qualitative stage, where conceptualisation of the solution is performed. Deliverables and activities are also geared away from solution-ended thinking.

R16.1.3: The methodology shall break down the problem structure (C8) (R16)

Problem structuring assists engineers in understanding and working through a problem. The first type of breakdown is in the time scale, where the work is segmented into stages. The next split is in disciplines, represented by the workstreams and system level work. Tiv-Model then breaks the problem through Macro, Mid and Micro-level perspectives. C-QuARK also acts as a problem breakdown tool.

5.3.17 Structuring (R17)

R17.1: Subdivision

R17.1.1: The methodology shall have a high level stratagem (NE2) (C8) (R17) and R17.1.2: The methodology shall partition information while maintaining transparency (MD3)

The macro-level is the main tool used to deliver this requirement; partitioning the problem is discussed in R16. The high-level stratagem is represented in the macro-level model and shows most of the functionality of the model. Information is partitioned from this in several ways. The existence of mid and micro-level models means that detailed information can be shifted out of view for consideration at another time. Work streams and system work level breakdown divide work by type, stages and Milestone Reviews divide work by timeline and theme.

R17.1.3: The methodology shall make tasks objective-focused (MR5)

The Tiv-Model is objective focussed, enforced by the emphasis on deliverables and milestones and rooted in the foundation of requirements-centric design. This objective driven nature is reflected in the WPM activities.

R17.2: Alternatives

R17.2.1: The methodology shall have a partially modular construction (R17) (I8) (MR4)

The modular construction of the Tiv-Model allows it to adapt to various types of project. The Investigative stage is modular to accommodate known designs or lack of contractual conceptualisation. The PRR exists to accommodate multiple systems of the same design. Review milestones change based on whether the project has human flight or not.

5.3.18 Compatibility (R18)

R18.1: Intra-Methodology

R18.1.1: The methodology shall be compatible with novel methods and findings (PB3) (R18)

This thesis has already discussed at length how it has included state-of-the-art findings in design research and how novelty is present throughout the design. Adopting models such as C-QuARK, determining requirements for the methodology and mitigation of industry adoption barriers are all examples of lessons from new findings. As for compatibility, it has already been noted that Tiv-Model is compatible with any design method given that it outputs the relevant deliverable.

R18.2: Organisational

R18.2.1: The methodology shall accommodate IT systems (MD1) (PB6) (C2) (C9) (R18)

Compatibility with modern technological requirements is key for design models and tools as the personal computer becomes an essential component to the design process. Compatibility with PLM systems, computer aided tools and the utilisation of the web app all count towards this.

R18.2.2: The methodology shall accommodate concurrent and centralised design (MR7)

The model supports these two types of engineering by including several elements. Knowledge Database, the inclusion of systems engineers, the Quantitative and Qualitative steps all support concurrency techniques. The Tiv-Model requires the use of these principles as it requires MPMs at the end of the Quantitative stage.

R18.2.3: The methodology shall be applicable to organisations within the target scope (C4) (R18)

The Tiv-Model avoids much of the organisational resistance through its flexibility in method and tool choice, it also provides information on adoption to help ease the process along. Organisational needs, such as information, resource management and planning are managed using the web app and knowledge databases. The Tiv-Model is also compatible with the current standards of aerospace design, including terminology and review milestones.

R18.2.4: The methodology shall use a common nomenclature (C4)

Tiv-Model uses a combined dictionary of aerospace and engineering terms, combined with a distinct glossary of its own. Terminology such as Deliverables, Stages, and workstreams are defined through the thesis, especially in Chapter 5.

5.3.19 Flexibility (R19)

R19.1: Degrees of freedom

R19.1.1: The methodology shall account for different forms of design (I3) (R19), R19.1.2: The methodology shall specify the extent of its flexibility (I8), R19.1.3: The methodology shall be able to adapt to project circumstances (I11) (R19) and R19.1.4: The methodology shall accommodate known solutions or legacy designs (PB5)

The flexibility of the Tiv-Model in this scope is that it does not support “over-the-wall” engineering very well. Tiv-Model is compatible with many methods so long as they deliver what is required in that subtask. It is modularity, Milestone Reviews and objective-based activity requirements give Tiv-Model a decent range of operation. Legacy designs are accommodated via the modularity of the Investigative stage, where research-based approaches can be removed.

5.4 Chapter 5 summary

In chapter 5, the goal was to define the solution, Tiv-Model, in the context of CSE design methodologies and present design decision justification.

The Tiv-Model is broken into three LODs; macro, mid and micro, each level represents a level of depth in the design process. Macro-level represents the general product development process broken into stages, work streams and work levels. These serve as the workflow representation for project leaders. Each item on the workstream is a deliverable or an activity, which are work packages to be completed by engineers and represented at the model's mid-level. These work packages are presented in a way that shows the designer what they need to do to complete that task, leaving little in the way of uncertainty. When a designer faces uncertainty in their process, they can refer to C-QuARK, a problem-solving schema made for design problems, which is also known as the micro-level.

The Tiv-Model incorporates many novel aspects in its construction, including a basis in state-of-the-art research, design centric elements, integration with modern PLM systems and a flexible goal-oriented problem approach strategy. With these elements in place, it was proposed that the Tiv-Model would benefit in several aspects of design. The engineers would benefit through ease of use, learning and transparency in the process where all information is available to users. The project benefits through better documentation and a concurrent/iterative approach to design. Knowledge databases aid the planning side of the project, while the product side benefits from the multi-perspective modelling focus. The organisation can keep their tools and methods when adopting the Tiv-Model, and in general the methodology aims to optimise cost through higher quality design.

The presentation of information on Tiv-Model is concluded by showing design justification and addressing the research-driven PDS. In Chapter 6, the Tiv-Model is validated by performing a series of studies and benchmarking it against the relative use-case performance of V-Model.

Summary at a glance

- Tiv-Model was defined in this chapter, comprising of three levels; macro, mid and micro-level
- These levels showed information pertinent to the operation of the model based on the role of the user
- Use of the model has a set of novel aspects:
  1) It uses academic lessons to benefit the industry
  2) Its structure is modular, and thus flexible
  3) It is validated using a new, repeatable V&V approach
  4) The model focuses on the needs of the engineer, such as procedural knowledge
  5) Goal-oriented task design means that methods are interchangeable
  6) Multi-perspective design approach to improve simulation result fidelity
  7) Integration with existing PLM systems, and comes with its own
  8) A range of other hypothesised benefits
- The means by which the Tiv-Model satisfies the Methodology Requirements Document are discussed

Next…

- The Tiv-Model undergoes the Validation Square, to verify and validate the model
- Chapter 6 includes comparative studies to verify the first 5 steps of V-Square

Chapter 6

Empirical Data and Benchmark analysis

To verify and validate The Tiv-Model, the Validation Square method was followed. The V-Square process is a literature identified tool used to build confidence in a design methodology. It was identified in Chapter 3 and how it was applied to the Tiv-Model was discussed here. To complete the verification steps in the method, a comparative study was performed between Tiv-Model and V-Model using student participants. This experiment and the results were discussed at the end of the chapter.

The comparative study was then followed up by a focus group study, to validate Tiv-Model and complete its evaluation. This is covered in Chapter 7.

In this chapter:

- **Validation Square method**
- **Verifying and Validating the Tiv-Model**
- **Comparative study overview and results**
- **Evolution of Tiv-Model through studies**

6.1 Methodology Validation

6.1.1 Validation Square method

Earlier in this thesis, it was established that the Validation Square (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000) would be used on Tiv-Model. Design methods and methodologies have the same core architecture and enough similarities that the two concepts are interchangeable with regards to verification and validation. Below, Figure 6-1 has the full V-Square diagram, showing how the tool is structured.

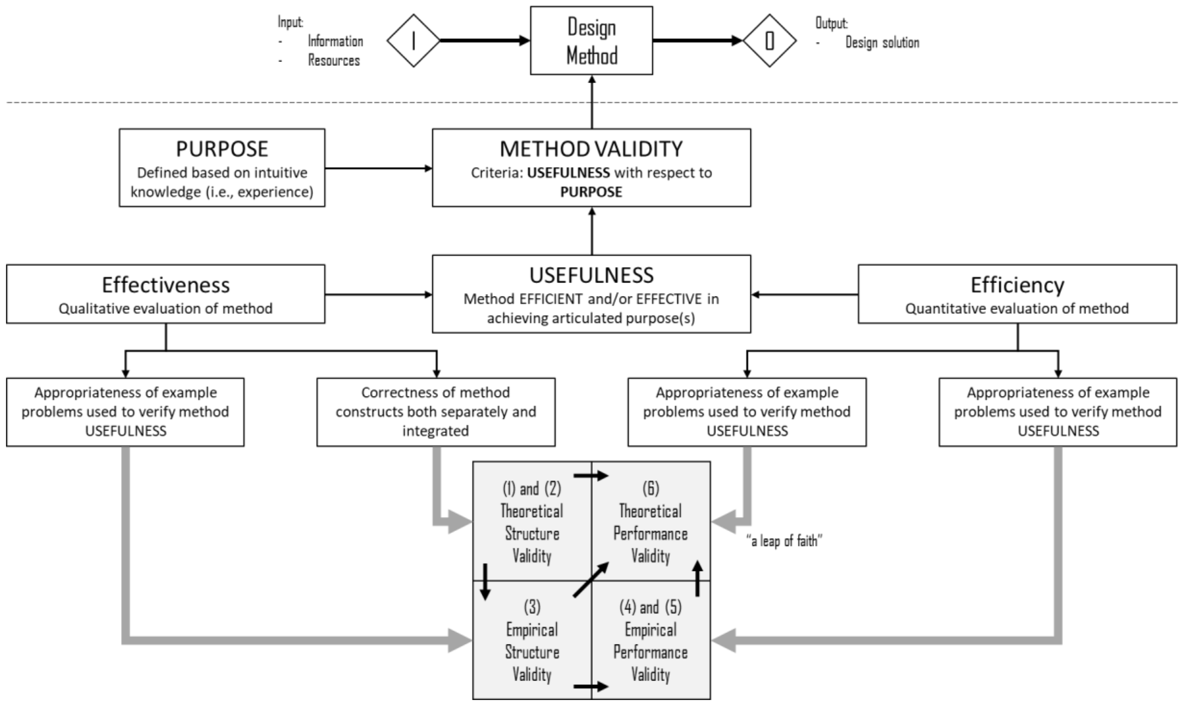


Figure 6-1 - The Validation Square, in full

The Tiv-Model's "usefulness" is first classified as the culmination of its perceived efficiency and effectiveness, which agrees with the literature. Effectiveness can be inferred from the methods or processes with which the methodology accomplishes its tasks. Effectiveness is proven by the validity of those methods within the problem context. The first two corners of the V-Square aim to measure "effectiveness", the theoretical structuring of the methodology is the first corner (top left) and the suitability of the example problems is the second (bottom left). Effectiveness, with respect to the V-Square is a qualitative measure of perception from the perspective of the users, stakeholders, and onlookers. Efficiency is the quantitative measure of the methodology with metrics such as time, cost, and failure rate.

The third corner of the square requires analysis the performance of the methodology with respect to the example problems. The final corner of the V-Square utilises the information learned from assessing the Tiv-Model. The information gained using this tool is conglomerated and extrapolated to imply that the methodology is practically "useful" for problems outside of the examples.

In practice, the V-Square is performed step-by-step to establish confidence in the methodology and create verifiable baseline assumptions. This advancing paradigm is a process encapsulated in V-Square by six key goals. These goals represent the requirements to prove validity.

Validation Square step 1 – Accepting the construct's validity (1)

When the structural validity of a methodology is accepted, it is based on the acceptance of its constructs (elements that make up the methodology, such as tools) within the user-base. This relies on academic and industry experience with these constructs to determine acceptance, validity, and usefulness. This can be a qualitative study regarding suitability, such as ensuring tools and methods are used in the right context. The informed opinions of industry leaders and users, literature and educated experience can be relied on to achieve construct validity.

Validation Square step 2 – Accepting method consistency

Once the methods and constructive components of the methodology are accepted as "valid", they must then be determined to be consistent when integrated. The aim is to show that these methods will logically produce the desired information output given the correct input. It is desirable to show that the information flow between methods and other constructs is suitable. It must be ensured that engineers are getting the correct information and that this information is suitable for the continuation of the design process. This can be accomplished through simple logical flow charts and diagrams that demonstrate how information evolves and where it is used.

Validation Square step 3 – Accepting the example problems

After the first two goals are accepted as being true, it can be assumed that the structural theory of the methodology is sound. Bailey et al. (Bailey, Mistree, Allen, Emblemsvåg, & Pedersen, 2000) call this corner “Empirical Performance Validity”, which qualitatively evaluates performance. The example problems to evaluate the methodology against are studied to determine if they are the most accurate ways of representing the intended problems. The intended problems are what the methodology is designed for. If the example problems are suitable and representative of the intended problems, then it is inferred that the methodology is suitable for the intended problems.

Validation Square step 4 – Accepting usefulness of method for some example problems

At this stage, the structural validity of the new methodology will have been fully inspected, transposing int work on the performance. It is here that more quantitative ways of determining validity are studied. From the previous goal, it was determined that the example problems are representative of the intended problems. Goal 4 asks that the usefulness of the example problems is determined. The authors note that it is important to determine usefulness in detail, as industrial and academic goals can differ, and the purpose of methods may not align. No specific suggestions are made for means to accomplish this, however some justification via literature may be used.

Validation Square step 5 – Accepting that usefulness is linked to applying the method

Although it can be determined that the methodology is "useful" in the example problem context, the degree of usefulness with respect to other variables must be realised. The authors suggest that each construct of the methodology be evaluated by measuring success of solutions with and without input from that construct. Using this logic, other methodologies can be used as benchmarks and compared against each other in analytical studies.

Validation Square step 6 – Accepting usefulness of method beyond example problems

Once the first 5 goals of the V-Square are complete, confidence has been achieved in the methodology building process. The V-Square operates on what is called "socially justifiable belief", where usefulness is measured by the perception of efficiency and effectiveness of the methodology. If most of the users feel that it works in the problem setting, then it works. This incrementally built confidence is used to generate a paradigm of model verification, building circumstantial evidence. By checking that design practice and theory was followed correctly, and that limited testing using representative example problems was performed and passed, it would have been reasonably demonstrated by this point that the methodology was verified.

After this verification has concluded, this evidence is used to extrapolate and prompt what the V-Square author calls a "leap of faith" into accepting usefulness for the intended problems. This can be done with the evidence already provided but can be bolstered by performing a validation step by using the methodology in the real-world problems or exposing it to expert critique. Once it is accepted that the methodology is useful in the intended problem space the methodology has been successfully validated.

Following some of the suggestions that the authors make for each of these goals, a validation and verification plan centred around the V-Square was created to demonstrate this process on the Tiv-Model. The following section documents that plan and elaborates on the justifications given.

6.1.2 Evaluating the Tiv-Model using the Validation Square

It is posited that the V-Square can be a standardised evaluation tool for design methodologies. The relativist logic used in V-Square reasons that this tool is useful for methods and methodologies where confidence can be built through experience and utilisation of said methodologies. This section outlines the verification and validation plan used for Tiv-Model. The intention was that this plan is used as both as a verification and validation plan for Tiv-Model as well as a guided demonstration of the V-Square.

The V-Square strategy shown in the literature is followed, aiming to conclude the 6 key goals set out by the tool with respect to the Tiv-Model.

Tiv-Model evaluation step 1 – Accepting the construct’s validity

As posited by Bailey et al, the verification process starts by ensuring that the construction of the methodology is valid. In Tiv-Model’s case, it must be accepted that the idea of constructs in a methodology are slightly different to that of a method but are comparable in the ways that matter. When compared to methodologies, methods have a smaller timescale and work scope; constructs and principles are defining elements within them. Similarly, for methodologies, working principles are constructs, but the verification of the discrete actions within them is too complex for the purposes of this thesis. Instead, the major elements of work within the methodology: methods and protocol, are examined. A protocol is a series of structured but generic high-level actions pertaining to a goal. Methods are similar, structured, and academically validated, but also more specific to the problem context. These are contextualised with working principles and objectives to create the core constructs which make up a methodology.

Providing evidence for the validity of the constructs is done through literature research. For each method or principle used in the Tiv-Model, an academic source can be found that provides credibility towards the concept. Table 6-1 shows the key methods that are used in Tiv-Model alongside citations that validate their existence.

Method type	Method	Citation
Management and planning	Project planning	(Lester, 2013)
	Design management	(Misra, 2015)
	Design methodology	(Pugh, 1988) (Best, 2010)
Research and specification	Literature review	(Blessing & Chakrabarti, 2009)
	Benchmarking/competitor analysis	(Dent & Storey, 2004)
	Design analysis	(Wilson & Mantooth, 2013)
	Case study	(Jerrard, Hands, & Ingram, 2002) (Thierauf, 1986)
	Experimentation	(Hall A. , 2011)
	Market research	(Economic Development Committee for the Mechanical Engineering Industry, 1971)
	Pugh's PDS elements	(Pugh, 1988)
	Cost-benefit analysis	(Snell, 1997)
Concept generation and refinement	6-3-5	(Wodehouse & Ion, 2012)
	TRIZ	(Renev & Cheehurin, 2016)
	Brainstorming	(Kazakci, Gillier, Piat, & Hatchuel, 2014)
	Rapid prototyping	(Chang, 2013)
	Free-body diagram	(Hibbeler & Fan, 1997)
Concept evaluation and selection	QFD	(Maritan, 2015) (Cohen, 1995)
	Decision matrix	(Pugh, 1988)
	FMEA	(Dale & Shaw, 1989)
	Feasibility analysis	(Kendall & Kendall, 2008)
	Sub-system relationship diagram	(Demoly, Dutarte, Yan, Eynard, & Ki, 2013)
Design evaluation	FEA	(Pidaparti, 2017)
	Kinematics	(Smith, 1943)
	Environment testing	(Neudeck, Prokop, Greer, Chen, & Krasowski, 2010)
	Scale prototype	(Baggen, Vaccaro, Llorens del Rio, & Padilla, 2011)
	Sub-system prototyping	(ISO/IEC/IEEE, 2015)
	Circuit modelling	(Odam, 1976) (Herrick, 1968)

Table 6-1 - Tiv-Model methods and literature validation

In the interest of time and conciseness, the explanation of validity is left to the citations and are not referenced within this document. It is crucial to note that Tiv-Model allows the user to determine which methods to use and when. Suggestions are made based on existing validity and the "best-in-class" understanding of the problem. There will be more methods, perhaps ones that better suite a niche problem. The Tiv-Model affords the user the means to make that judgement and opts to work around it. The validity of the construction of methods is accepted because the academic legwork towards validation has been done already.

Protocol on the other hand is largely dependent on the specifics of the methodology in question. First, the long-term protocol is investigated. In the largest of scopes, the protocol of a design methodology is equivalent to the design process model. This is called the macro-level protocol, represented on the Tiv-Model as "stages" and "tasks". This can be validated simply by aligning the Tiv-Model with the design process model, shown in Figure 6-2. If the design process model is accepted as useful, and the Tiv-Model closely follows that protocol, thus at the macro-level the Tiv-Model protocol is also perceivably valid.

Figure 6-2 - Cross' design process model stages next to Tiv-Model's stages

The protocol at the work-package level of the methodology, which covers the mid to short-term goals, is called the mid-level protocol, represented on the Tiv-Model as "subtasks". Mid-level protocol can be validated by identifying the major tasks within each stage of the design process model and aligning them with the mid-level protocol that is shown in the Tiv-Model. Table 6-2 below shows key sub-tasks within the Tiv-Model aligned with their design process model equivalents. Once again, the validity of these constructs is proven by showing that they (or their equivalent) are already considered valid either by research, demonstration, or existing socially justifiable acceptance.

Category	Relevant Activity or Deliverable	Citations
Requirements	Mission Requirements, System Requirements, Sub-system Requirements, Security Requirements, System Requirements Review	Evolution of requirements documentation (Grady, 2000) (NASA, 2020) (American Institute of Aeronautics and Astronautics, 2003) (Pugh, 1990) (Pugh, 1988)
Feasibility	Feasibility study, Technology Development, TRL Report, Legacy Project assessment, Mission Concept Review	Use of feasibility studies in industry and academia for complex systems; (American Institute of Aeronautics and Astronautics, 2003) (Macdonald, 2014)
Estimation	ROM Cost, Scope setting	Prevalent use of cost analysis in projects inside and outside of engineering (Collier & Glagola, 1998) (Hunt & Butman, 1995) (Chang, 2013)
Planning	Initial planning, WBS, Management Plans, Technical Plans, SEMP, Schedule	BSI standard practice of project management in engineering (Lester, 2013) (NASA, 2020) (Means & Adams, 2005) (Lester, 2013)
Contracting	Operational agreement procurement, Formulation Agreement, AoO, RFP, Contract Award, System Acceptance Review, Statements of Work	Mandatory agreement between parties for work and components of agreements (American Institute of Aeronautics and Astronautics, 2003)
Concept design	Conceptualisation, CopOps, Architecture design, SBS, Preliminary Design Review, System Definition Review	Sub-function design as practice in complex system projects (Misra, 2015) (Andrews, 1998) (Demoly, Dutarte, Yan, Eynard, & Ki, 2013)
Concept refinement	Design Refinement, Iteration of work	Component of continuous improvement (Bititci & Nudurupati, 2002) (Taghizadegan, 2006)
Low-level engineering	Software design	Data flow standard practice in software engineering (Li & Zhang, 2013)
	Component design, Critical Design Review	Most basic task in circuit design, computerised (Odam, 1976) (Herrick, Electronic circuits, 1968)

		(Houghton, 1995)
Simulation	Multi-perspective model	Innovative method for robust virtual prototyping (Yan X. , 2003) (Yan & Zante, 2010) (Stuart, 2002) (Shigley, 1969) (Mallik, Ghosh, & Dittrich, 1994) (Hooi. Tan, 1986) (Zipfel, 2014)
Manufacturing	Bill of Materials, Procurement, Long lead items	BoM critical to project, early and continuous modification important to cost robustness (Rowell, Duffy, Boyle, & Masson, 2009) (Watts, 2011)
	Production, Assembly, Integration, Test Readiness, Production Prototyping, Production Readiness Review, Test Readiness Review, Flight Readiness Review	Common practice for manufacturing (Griffiths, 2002) (Boothroyd, Dewhurst, & Knight, 2010) (Molloy, Warman, & Tilley, 1998) (American Institute of Aeronautics and Astronautics, 2003) (Koenig, 2007)
Use	Operation, Launch	Mandatory component of product use
Upkeep	Tech Refresh, Software support, Integrated logistic Support	Specific maintenance challenges for space-faring constructs (Richards, 2007) (Leete, 2002) (Xu, Liang, Li, & Xu, 2011) (Ogilvie, Allport, Hannah, & Lymer, 2008)
	Mission reports, Data archiving, Data acquisition	(Watts, 2011)
Disposal	Decommissioning and Disposal, Disposal Readiness Review	(Harkness, et al., 2014) (Straub, 2014)

Table 6-2 - Tiv-Model activities and citations

Again, in the interest of time and conciseness not every subtask in Tiv-Model is listed. Key sub-tasks are shown but additional sub-tasks are decided upon by the project/program manager, system design leader or user. If it can be accepted that the Tiv-Model mid-level protocol is equivalent to existing design process protocol, and the existing protocol is accepted as valid, it can then be inferred that the mid-level protocol is valid.

The final class of construct present within the Tiv-Model are the principles by which the Tiv-Model is guided. These principles have been extensively covered in the initial literature research of the thesis, but a short recap is shown in Table 6-3.

Principle	Citation
DfX	(Pahl & Beitz, 1996)
Multi-perspective modelling	(Yan & Zante, 2010)
Concurrent engineering	(Clausing, 1994)
Iterative design	(Spillers, 1975)
Complex systems design	(American Institute of Aeronautics and Astronautics, 2003)
Product Lifecycle Management	(Stark, 2015)
Goal-oriented activities	(Pahl & Beitz, 1996)

Table 6-3 - Principles of Tiv-Model and literature validation

Using literature citations and reasoning, independent construct validity can be confirmed for the structural elements of the Tiv-Model. The next step is to ensure these constructs are used in the correct, consistent context.

Tiv-Model evaluation step 2 – Accepting method consistency

Next, after proving that the constructs within the Tiv-Model work independently from one another, evidence and reasoning was provided to suggest that they work in harmony towards a common goal. The V-Square author makes suggestions with regards to mapping out the information flow in a logic flow chart. The logic diagram, shown in Figure 6-3, maps the information flow between key tasks throughout the model to show how information is utilised. It is then demonstrated that this logic runs parallel to the conventional understanding of the design process by aligning the Tiv-Model to the traditional design process.

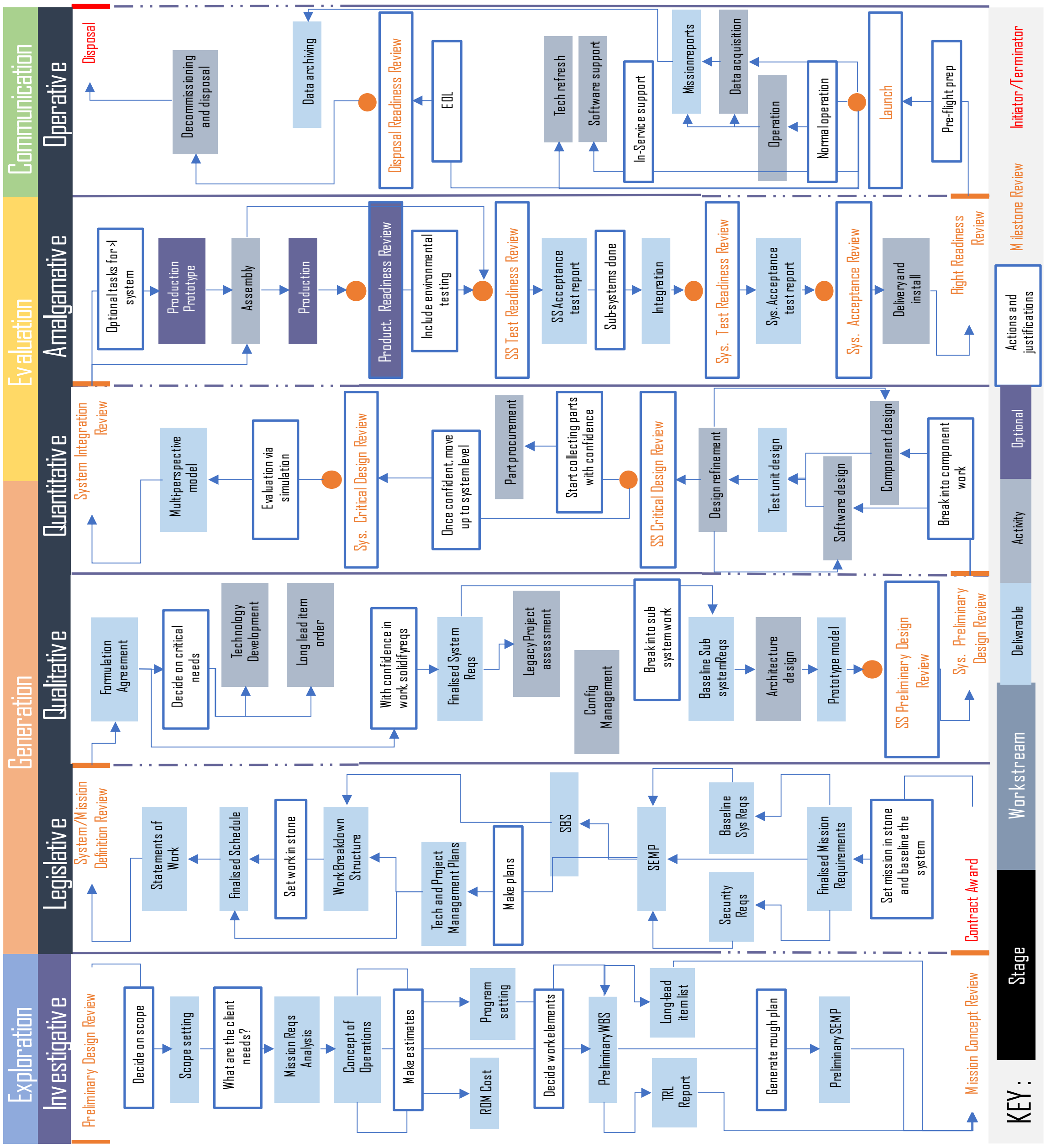


Figure 6-3 - Logic flow chart of information within Tiv-Model

The key deliverables represented on the Tiv-Model's macro-level are highly representative of the information flow in this diagram. One of the operating principles of the Tiv-Model is its transparency to the user and the key deliverables not only offer suggestions for workflow but also provide evidence for consistent inter-method relationships.

By showing the flow chart in this way, “method” consistency can be drawn between the Tiv-Model and existing design process models. If the existing engineering design structure of methods can run parallel with Tiv-Model’s structure (with regards to key outputs between stages), then it can also be considered a valid logical structure.

Tiv-Model evaluation step 3 – Accepting the example problems

The “example problems” are the problems that Tiv-Model is exposed to during testing. Accepting that these example problems are suitable for testing the methodology first began with defining the intended problems, the situations that the Tiv-Model is designed for. As discussed throughout this thesis, Tiv-Model has several layers of intended problems. Here some of the key features of the intended problems are identified as discussed in Chapter 4:

- Large in scale/scope
- Engineer-to-Order
- Complex assembly structure
- Costly
- Prototyping limitations
- Function/sub-function driven solutions
- Concurrent
- Large personnel and resource utilisation

If it can be determined that the example problems reflect some of these properties (despite the scaling of the problem) inferences can be made on the suitability for the intended problems based on how Tiv-Model handles the example problems. The opportunities that are available to the author of this thesis are explored at this time and an interesting proposal is encountered.

Several opportunities were presented, involving students from the author’s university engineering department, Design, Manufacturing and Engineering Management. The author had the chance to get involved with the teaching of several classes of students and become involved with individual projects of a handful of postgraduate students. All projects involved the development of robotic systems, most of which were for terrestrial applications. One project was to develop a robotic arm/manipulator that lays and applies sheet icing to cakes on an automated assembly line. This is an example of a project that incorporates several of the key features from the list above. Another suitable opportunity was to teach a class of undergraduates and postgraduates undertaking a group project. Students were to develop an agricultural crop inspection rover system with several sub-function modules. This project not only satisfied the solution criteria on most levels but provided the critical management context that was desired. The main differences between the target feature list and these two example problems was scale. The scope was at least a degree in magnitude smaller, cost and personnel (student) utilisation was small, but still contained the core design team ingredients, and the complexity is much more manageable. One could compare it to the "Mechatronic" type of solution, identified in Chapter 2.

It was decided that both the robotic manipulator and the student rover project were a good basis for example problems due to the shared properties between them and the intended problem area. Thus, the arm and rover projects were used as the example problems for the V-Square method. After the example problems were decided, the means of applying the Tiv-Model to the example problems was then planned.

Tiv-Model evaluation step 4 – Accepting usefulness of method for some example problems

As suggested by academia, usefulness of the Tiv-Model for the example problems may be demonstrated through case study. As mentioned in the previous segment, access had been given to that opportunity through the university department via existing projects. It was proposed that a case study based on a piece of space-faring hardware would provide some insight into the use of Tiv-Model within the example problems. This introduction of this prescriptive study is covered in section 6.2.1.

To briefly conclude the results of the case study; the Tiv-Model’s components appeared to work well for a complex project, however some of the planning and communication aspects of the model could not be utilised in a one-person project and thus could not be evaluated. The design principles baked into the Tiv-Model were the most useful, with the problem-solving schema and quality improvement principles demonstrating their effectiveness. Through merit of the solution generated in these projects (i.e., the student followed the process and emerged with a viable solution) it was shown that the methodology is indeed useful for the example problems. For a complete summary of the case study results, see section 6.3.1.

Tiv-Model evaluation step 5 – Accepting that usefulness is linked to applying the method

As the example problems had been established and applied, the next step of the V-Square method was to determine if the application of the Tiv-Model is the specifically useful component. This was perhaps the most complicated step in the V-Square method. Another opportunity was established within the university, involving managing the workload of several classes of undergraduate and post graduate students, all with the same agricultural rover project. This allowed the unique opportunity for a series of parallel comparative studies to be performed between the Tiv-Model and another candidate model. By measuring the student's perceived usefulness of the model they are using, and performing a t-test on the sample data generated, two groups of students (using two different design models) could be compared. Iterative studies would then provide ample opportunity to tweak the Tiv-Model and test parameters to improve result accuracy. This series of comparative studies is introduced in section 6.2.2.

In short, the comparative study took place over three phases of test instances, using over 100 responses, and showed marked improvement of the Tiv-Model compared to the benchmark model in 13 out of 24 performance categories. In phase 1 the Tiv-Model underperformed but with each study iteration changes were made to the Tiv-Model which improved its relative scoring. Since effectiveness is a user perception driven metric, as per V-Square's logic, it can be inferred that the student's opinions on those matters were indicative of actual effectiveness, measured by weight of each student's opinion over many samples. If Tiv-Model was proven to be as good as or better than its benchmark, which is already validated through trial and testing in industry, it can be assumed that Tiv-Model is valid in the same way. Surprisingly, by the final study iteration, Tiv-Model not only matched the benchmark model in some ways but also out-performed it in most. Therefore, the evidence suggests, with at least 95% confidence, the perceived effectiveness and/or efficiency experienced when using the Tiv-Model is indeed linked to the application of the model and not some other factor. For a complete summary of these study results, see section 6.3.2 to 6.3.4.

Tiv-Model evaluation step 6 – Accepting usefulness of method beyond example problems

At this point, the verification of the Tiv-Model was complete. The components of the Tiv-Model and their logical flow were validated, so too the Tiv-Model in the example problem setting. The remaining action to prove validity of the Tiv-Model was to make the logical step towards accepting its usefulness in the intended problem space. To achieve this 6th goal, the previous 5 steps laid foundations, providing verification of the Tiv-Model in several forms. In short, these steps were:

1. The types of constructs that made up the Tiv-Model were methods, protocols, and principles. The methods selected in Tiv-Model were already considered valid academically and industrially. The protocols used were validated by comparing Tiv-Model's high-level stages with the existing, valid design process stages. The validity of Tiv-Model's principles was reflected in the literature review within this thesis. Since these construction elements were proven valid, the goal of step one has been achieved.
2. The information flow and method logic of the Tiv-Model is followed to prove that the constructs are providing the contextually correct information. This information flow is demonstrated using external and internal deliverables, a critical concept within Tiv-Model. By comparing the context of the Tiv-Model to existing engineering design processes, the goal of step 2 was achieved.
3. Key features of the intended problem space were determined, and opportunities were sought for that allowed the Tiv-Model to be placed into a project that possessed some of those key features. Two example problems were found; the first was a study and design of space fairing hardware within the university. The second was a class-based series of projects for groups of students to create an agricultural rover. These two example problems were close enough to the intended problem space in some of the key areas, while also being effectively cost-free and easy to organise within an academic environment.
4. The space fairing student project was organised to explore the effects of the Tiv-Model when applied to a robotics project. The model is seen as "effective" in the sense that it

delivers the promised solution through use of its process for this problem, as evidenced by the project outcome. However, usage of some of the key features were notably lacking due to the limitations of a one-person project. Despite not being able to evaluate those aspects of the model, the goal for the step 4 was achieved.

5. Through three phases of comparative studies, with feedback given through surveys, the performance of the Tiv-Model was empirically verified against another benchmark model. Participants respond to various questions about beneficial aspects of the two models and the answers given were compared. The iterative nature of these experiments allowed for improvement of the Tiv-Model between phases, to evolve the model based on user feedback. It was shown that Tiv-Model was as good or was better in every aspect studied, beating the benchmark model with 95% confidence in 13 out of 24 aspects. Thus Tiv-Model was confirmed both efficient and effective in these regards empirically over 100+ samples. After studying the Tiv-Model within the example problems, step 5's goal was achieved.

Through provision of suggestive evidence in these five aspects, the "leap of faith" may be taken to validity. However, to bridge the gap for this logical step, one further study would be used to expose the Tiv-Model to the intended problem space. It was noted that the missing component from the previous studies was actual industry perspective. The participants in the comparative study were students, and it was exceedingly rare for students to have expertise in industry before being in the classroom. Thus. it was decided that an industry focus group would help shine a critical and expert eye onto the Tiv-Model to alleviate any industry-based concerns for the model. This study is detailed in Chapter 7.

The quick summary to this study was that there were several primary conclusions to be drawn from the discussions in the focus group. Firstly, and most importantly, the Tiv-Model macro level did not appear to capture the amount of information expected by the industry professionals. Secondly, there was ambiguity surrounding the applicability and responsibilities imposed on parties by Tiv-Model during its implementation and use. The final observation to be made from the focus group was that there were several aspects of design that were not captured. To address the criticisms of the Tiv-Model, some moderate final changes were made to satisfy concerns.

After all these verification steps, within the expectations of the V-Square method, Tiv-Model was accepted as suitable and effective for the example problems, which were concluded to be representative of the actual problems. Therefore, it was concluded that Tiv-Model, after some changes suggested by industry veterans, was suitably effective and efficient enough for the intended problem area.

This concluded the V-Square's process in proving that the Tiv-Model is verified and valid, the aim of which was to highlight and demonstrate some standardised means of evaluating engineering design methodologies. The intended purpose of this standardised validation method was to encourage academics to use a familiar strategy to evaluate their methods, and to encourage industry to recognise the validity of academic methods that pass this evaluation process. The following thesis sections detail the processes taken to come to these conclusions in more detail.

6.2 Experimentation

V-Square's penultimate step requires the Empirical Performance Validity of the methodology in question is evaluated. This can be done in a few ways, but the most robust method for doing so is to perform some means of comparative statistical analysis. This analysis, and other studies, were performed in a series of experiments aimed to benchmark Tiv-Model against a competitor.

The entire set of studies for Tiv-Model consist of:

- 1 observational case study on the use of Tiv-Model in a mechatronic project
- 3 generations of statistical comparative studies
- 1 feedback focus group study

The comparative studies were iterated as it allowed improvements to be made to the Tiv-Model based on feedback from the previous group. In doing so, a feedback loop is created that enabled continuous improvement of the methodology whilst it was being developed for use.

6.2.1 Case study

In the first case study of the Tiv-Model, the aim was to provide a satisfactory answer to V-square's 4th goal, that the methodology is suitable for the kind of work the example problems represent. This is gauged by screening the Tiv-Model in a trial exercise using an academic project aiming to develop space mechatronic hardware. The project was already in an early phase of the design process; thus some retroactive application of the model was performed. There were no group components of the work which eliminated the potential to evaluate personnel management.

The project was a spin-off of the University's existing work on SIROM, an active, fail-safe connection interface for spacecraft and Active Payload Modules (APM), commissioned by the ESA. This situation contained the critical elements of the engineering design process, ending just before the physical realisation of the product. This allowed the application of design process models to this workload with little compromise in applicability. The kinds of designs undertaken were relevant to the field that Tiv-Model is applicable for, space systems. The Tiv-Model was adjusted in such a way that would be suitable to the project needs.

The goal was to apply the Tiv-Model to the project in-progress, making retroactive changes where needed, and improving the design quality using Tiv-Model. The advantage of this kind of case study was accessibility in the academic environment. The disadvantage was the limited scope of the project, as it was a solo affair that had no goal of going into manufacturing or high-fidelity testing. Thus, those components of the Tiv-Model were projected based on assumptions made in the project. The output desired from this study was a reflection on the use of the methods, principles, and other aspects of the model. This was acceptable within the setup as the aim was to get a rough consensus on how the methodology functions under load.

This rough evaluative case study aimed to support the V-Square's 4th requirement. By using the methodology in a mock version of the sample problems, the suitability of the Tiv-Model was determined for the example problems. Simply put, if it worked for this problem, it could reasonably be assumed that it would work for other, similar problems. The small scale of the case study allowed a personal approach and extended scope of investigation.

6.2.2 Statistical analyses

The second type of study utilised for the V-Square approach followed a statistical analysis strategy. This kind of study was accomplished through the utilisation of high participant numbers and a structured environment for study. Thus, a classroom project was targeted as a satisfactory scenario that adhered to these requirements.

A classroom of engineering students was tasked with the design and development of a mechatronic system as part of their curriculum. The students were to research, design, and prototype subsystems of an agricultural rover that can take coordinates from an inspection drone, drive through a crop field to those coordinates, inspect the surroundings for damage and deliver new crop seeds to the target area. Students grouped for this assignment and were given until the end of the semester to accomplish, document and present their approach.

Randomisation and group assignment

The classroom was split into assignment groups, between 6 and 12 students depending on the class (Postgraduate and undergraduate) and the number of students in attendance to that class. The class groups and rough sizes (+ or – 1 student) are shown in Table 6-4 below.

Student type	Group size	No. of groups
Post/Undergraduates, Phase 1	17~	6
Undergraduates, Phase 2	12~	7
Postgraduates, Phase 2	10~	2
Undergraduates, Phase 3	45~	2
Postgraduates, Phase 3	7~	2

Table 6-4 - Survey group sizes

In the undergraduate and mixed classes, the group composition was highly varied from many backgrounds, and the number of groups meant that some consideration was paid towards composition. Care was taken to ensure that each group contained at least one member from each discipline (design, electronics, mechanics, etc), so that there were no missing knowledge requirements. This was a selective process based on the background of the student, with no other selective procedures used. For this reason, the is selection process can be considered random for the purposes of the study. Phase 3 of this case study seen a shift in how the undergraduate class was organised and groups were subdivided, although the nature of the work was the same.

In both postgraduate classes, students were assigned a group number based on their position on the class register, arranged alphabetically. There were only ever two groups in the postgraduate classes due to the small numbers in the classroom, and students were assigned the group number 1 or 2. This method was suitable as their backgrounds were mildly varied but a sizable amount of the students had less focus on design education and instead came from an even mix of mechanical/electronics backgrounds. This distribution of skills meant that this selection method gave each group at least one student from each background area.

Groups were considered as either a control, or an experimental group based on the design methodology they were given. The way design methodologies were assigned to groups was varied by the circumstances. In phase 1, groups could pick either methodology to use after they had been taught both in a classroom environment. This process was discontinued in phase 2, where groups were assigned equally amongst both postgraduates and undergraduates (1 additional group chose V-Model use due to odd numbers). For phase 3, students could choose their model in the undergraduate class. However, it was predicted that V-Model would be picked by all groups, since this is the model they were already very familiar with. Consequently, the postgraduate class was assigned with the Tiv-Model and the undergraduates were given the V-Model, although both were taught in-class. This resulted in varying splits in population, phases 1 and 3 have majority V-Model involvement, phase 2 has an even split as possible.

Teaching of the models

The teaching of the two models was identified as a significant precursor to use in terms of understanding, perceptions, and performance. The goal was to construct a learning experience that would ultimately deliver the best possible understanding of the two models. However, there were constraints within the classroom approach to be considered. Firstly, the amount of class time one can dedicate to the learning of the methodology is limited. The students can learn the methodologies as part of the class, but there were a finite number of lessons available where the remaining class content must be taught. The typical class structure was a weekly 4-hour seminar with 2 hours of class time and 2 hours of workshop time. The course content was considered when deciding how long to spend teaching the students the two methodologies, and thus a compromise was met on the teaching plan:

- 2 lectures lasting one hour each
  - First lecture revisits the design process in detail
  - Second lecture the week after covers the V-Model and Tiv-Model
- A hands-on workshop, 1 hour long, focusing on the mid-levels of each methodology
- Weekly drop-in sessions
- Continuous online and offline support and contact
- Provision of reading material outside of class

The class lectures were the foundations of the learning experience for the students, where they would learn the foundation information and context, allowing them to understand the methodologies and why they are necessary. The first lecture was a re-visit to the design process, this lecture taught standards such as terminology and context to be set into the class. This brought the students to a base level of understanding of the design process and its components. For students with design experience, this would be a chance to brush up on knowledge learned in their 1st and 2nd year classes. For students without, the lecture would be a quick way to establish the required understanding of the design process to use the models. The time constraints meant adoption of a visuals-driven approach to teaching. Core concepts were demonstrated through PowerPoint, images, analogies, and examples, rather than text. The lecture covered the design process, each of the components of the process (research, conceptualisation, design, output), why and how each of these tasks add value to the design and some methods that are useful. The first lecture thus, aimed to equip the students with the essential knowledge and context required for understanding the two models used in the project. This lecture also delivered the assignment content which, aside from giving context to the students, engaged them with the project early.

The second lecture followed up with a quick refresher on the previous lecture's content, then the students were taught Tiv and V-Model. The teaching of the two models was approached similarly. The students were first introduced to the idea that the design process is flexible at the method levels, depending on what kind of result is required, and existing examples were explored. The macro, mid and micro-levels of the two design models were then shown. Each model was addressed as a whole, discussing the over-arching premise for each, and then compared. Afterward, conclusions were drawn about what these differences mean, and cross referenced back to previous models, include the design process models presented in class.

Immediately after the second lecture, the remainder of the class lecture time was occupied by a hands-on workshop. This workshop presented a small design challenge to the students, which was to perform a portion of the project conceptual design as part of their group assignment. The goal was to teach the students how to operate and document their project using the macro and mid-level models. These parts of the methodology were selected as they were core components of the Tiv and V model, it was assumed that micro-level instructions were simple enough to follow.

The students were tasked with using their understanding of the design process to determine how much of the design model they will use for their project. The course expects the students to deliver a prototype of some subfunction and some manufacturing drawings, so the correct answer was to cut the macro-level to the Quantitative stage. They then filled out the work package modules that would entail the conceptual design tasks. Students would specify the methods they would use, the general procedure and deliverables and relate these back to the design process.

The level of adherence that was expected of the students was explained through this demonstration. It also taught them how they could customise the modular aspects of the methodology and remove any doubts they have about the model.

After the workshop had finished, the students were handed reading material specifically made to teach the students about the model, its anatomy and how to use it. They were given two documents on their assigned model, the first was a descriptive reference document that explains all functionalities of their assigned methodology. The second document acted like a" how-to" or instruction manual for their assigned model. The intention behind these documents was to guide the students through the setup of their model to use in the class project.

As the phases of the study were iterated, thus the quality and effectiveness of the teaching was continuously improved overall for more robust results. Iteration of the comparative study happened across three phases. The intent was to improve both the Tiv-Model and the testing procedure through each phase, learning from observations and feedback given from the previous phase. This happened in several cases through the experimentation and proved an invaluable strategy for the development and refinement of Tiv-Model.

Data acquisition

From the comparative studies, the aim was to gather data through formal survey data, which was important to the improvement of the methodology. The literature suggested the use of quantitative metrics can help industry decide which method or methodology to use. To satisfy this requirement, qualitative data was turned into quantitative data where possible via survey results.

The survey posited 20 questions (23 in phase 2 and 3) to the students regarding their perceptions of the model they used and how they felt it performed. The survey was designed to address some of the relevant requirements developed from the literature. Table 6-5 shows the list of questions given to the students, alongside the requirements they aimed to generate information for.

Question	**Requirement**
Overall, I found the methodology difficult to use	Efficiency
I would definitely NOT use this model to develop mechatronic systems	Problem Specificity
I would use this model instead of Pugh's TDM if I have to develop a mechatronic system	Competitiveness
I found the rules of the model clear and easy to understand	Learnability
I found that the model was suitable for this kind of project	Applicability
I found that my existing knowledge worked well with the model	Comprehensibility
I found that I was limited to specific means or methods in order to achieve my goal	Flexibility
I believe that the model would reduce the effort required to produce mechatronic systems	Efficiency
Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems	Effectiveness
I am NOT confident about applying this method in practice	Comprehensibility
I found it difficult to apply the model to the project	Applicability
Using this model would make it more difficult to complete mechatronic projects	Efficiency
This model would make it easier for designers to produce mechatronic systems	Efficiency
Using this model would make it easier to communicate concepts in a mechatronic project	Reliability
I found the model easy to learn	Learnability
Overall, the model's information was well presented	Comprehensibility
I would use this model again in a general product development project	Repeatability
I found the model complex and difficult to follow	Comprehensibility
Overall, I found the model to be useful	Effectiveness
Overall, I found that the model freely allowed me to make design decisions	Flexibility
The Macro-level model was useful for this project	Effectiveness
The Micro-level problem solving technique was useful for this project	Effectiveness
The Mid-level task management was useful for this project	Effectiveness

Table 6-5 - Survey questions

Participants in the survey would answer each of these questions with one of five options of agreement, disagreement, or uncertainty. The answers of the survey were aligned with the general feelings towards the methodology without the participant having to quantify them specifically. This led to an easy-to-answer survey, although these subjective answers alone did not provide the kinds of data needed for statistical analysis. The literature points in the direction of methodology evaluation's future, the use of quantitative data for presentation of performance to industry. Thus, this survey data was turned into something that could be quantified.

Using a metric called "Agreement level" the subjective summation of feelings towards an aspect of the Tiv-Model could be categorised into discrete values. Negative values are used to represent disagreement, null values to represent uncertainty and positive values to represent agreement. Each whole number from 0 is one degree of magnitude meaning that a range of -2 to 2 is used in whole numbers. The agreement map is shown in Table 6-6.

Survey result	Agreement level
Strongly Disagree	-2
Disagree	-1
Not sure	0
Agree	1
Strongly Agree	2

Table 6-6 - Agreement level

Agreement level is NOT the same as satisfaction, as agreement level only measures the subject's agreement with the question presented. Questions may present a negative experience context, which means agreement would indicate a negative satisfaction rating. Transforming the subjective terms into a relative numerical scale enabled statistical analysis of opinions. This was demonstrated empirically by forming a hypothesis.

Hypothesis

As per traditional statistical tests, two hypotheses must be developed in the comparison between the two methodologies. Thus, each survey question has a null hypothesis and an alternative hypothesis.

The null hypothesis is the default assumption, in this case, that the use of a methodology does not have a significant impact or difference to the design process, worded as:

> *"The mean agreeableness of the results from those who used the Tiv-Model and those who used V-Model will remain the same."*

This is represented through the average agreement level of the students taken for each question. If Tiv-Model users had a higher average agreeableness compared to V-Model users in a question, then this could be represented statistically through the average agreement level. This was represented short-hand as "$\bar{x} = m$", where "$\bar{x}$" is the average of V-Model agreeableness for the question, and "m" is the Tiv-Model agreeableness.

The alternative hypothesis was the expected outcome of the study. For these studies, the alternative hypothesis was the same for each comparative question:

> *"The mean agreeableness of the results from those who used the Tiv-Model and those who used V-Model will differ."*

This could be represented mathematically in the hypothetical statement "$\bar{x} \neq m$". It was hypothesised that the agreement level of each model would be different from each other. Note that ">" or "<" was not specified in this case. The alternative hypothesis statement was open to the idea of V-Model having a higher agreeableness level.

Using a numerical metric, the null hypothesis could be accepted or rejected using the non-paired, two tailed t-test method with no assumptions made for similar variances. (Quirk, 2014) The data samples were collated in Microsoft Excel, which performed the "TTEST" function and calculates the p-value. With the inclusion of other data, the null hypothesis could be accepted or rejected using this method.

6.3 Experiment results

The experiments were split into two studies. The first case study focused on the impact of the Tiv-Model on a project. The aim of this was to test and understand the interaction of the model with a suitable design project. This information would then be used to satisfy the 4th requirement of the V-Square. The second case study set was a series of group case studies performed with student group projects. The study focused on the opinions of students with regards to the Tiv-Model. These were directly compared to opinions on users of the V-Model, the control element of the study. The results were quantified and compared numerically to determine the perceived effectiveness and efficiency of the Tiv-Model vs the V-model. This would be used to satisfy the 5th requirement of the V-Square.

6.3.1 Project case study

This case study took an existing project that had started development within the university's DMEM department. As part of the academic process, SMeSTech began work on a design for a spacecraft module connection interface. This was based on work done for an ESA grant, using the thesis author's personal research. (Yan, et al., 2018) The physical interface's design allows a spacecraft or module to interlink with other craft elements with the same interface. This would allow data, power, and thermal load to be exchanged between the two connected elements and enabled a series of craft modules to become a cohesive system. The goal was to pave the way for module-based spacecraft, manipulated by a multi-purpose arm that could connect to the interface. This would incentivise standardised and compartmentalised design as well as in-situ servicing. This provides numerous benefits such as increased potential mission lifetime and reduced risk of early mission failures.

The goal with this case-study was to apply Tiv-Model to the project, hypothetically and practically. Hypothetical application was reserved for components of the project that had already happened or would not happen within the scope of the case study.

The aim was to apply the following components of Tiv-Model:

- High/Mid-level project planning
- Low-level problem solving (C-QuARK)
- Knowledge databases
- Multi-perspective modelling
- Readiness Reviews
- Deliverables

The Tiv-Model was followed stage-by-stage in this case study, starting with the Investigative stage.

Investigative

The starting point of the Investigative stage was before any formal work had begun. Usually in an industry scenario, the client would give their brief to mark the beginning of the project. In this case, there was a research drive.

Initial feasibility research was conducted at this point, and the bulk of the detail research work was spread throughout the point in time where the Legislative stage would be. The feasibility study was replaced with cursory analysis of existing research gaps.

Once complete, rough planning and actualisation of a plan was underway. This included solidifying the research methodology and setting up the Tiv-Model.

High-level project planning

The short-term goal of the design project was to generate academic literature, and thus the scope of the material was limited. Prototyping and small-scale testing was possible; however, manufacturing and delivery of a working interface was not required for this academic exercise. Knowing this, useful stages of the Tiv-Model for this project are shown in Figure 6-4. Note that the visual aspects and deliverables from this version of the Tiv-Model are different. This project was based on an earlier variant of the model, where the workstreams and deliverables were slightly different, and the Amalgamative stage was replaced with the Evaluative stage.

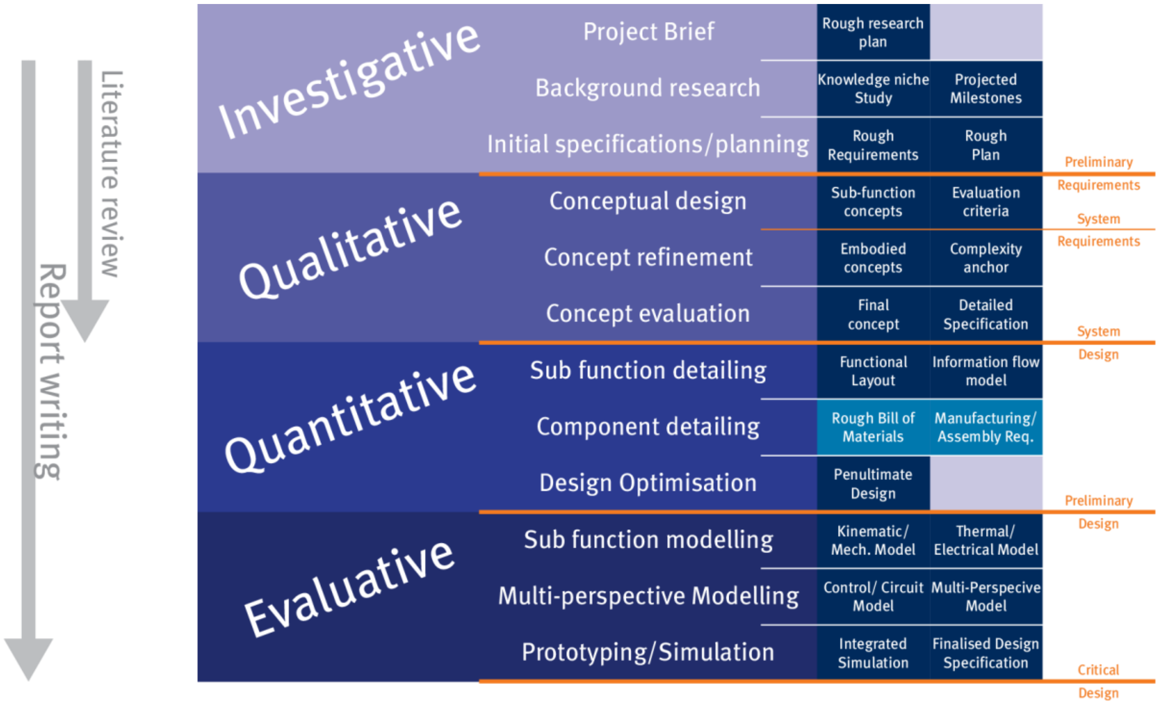
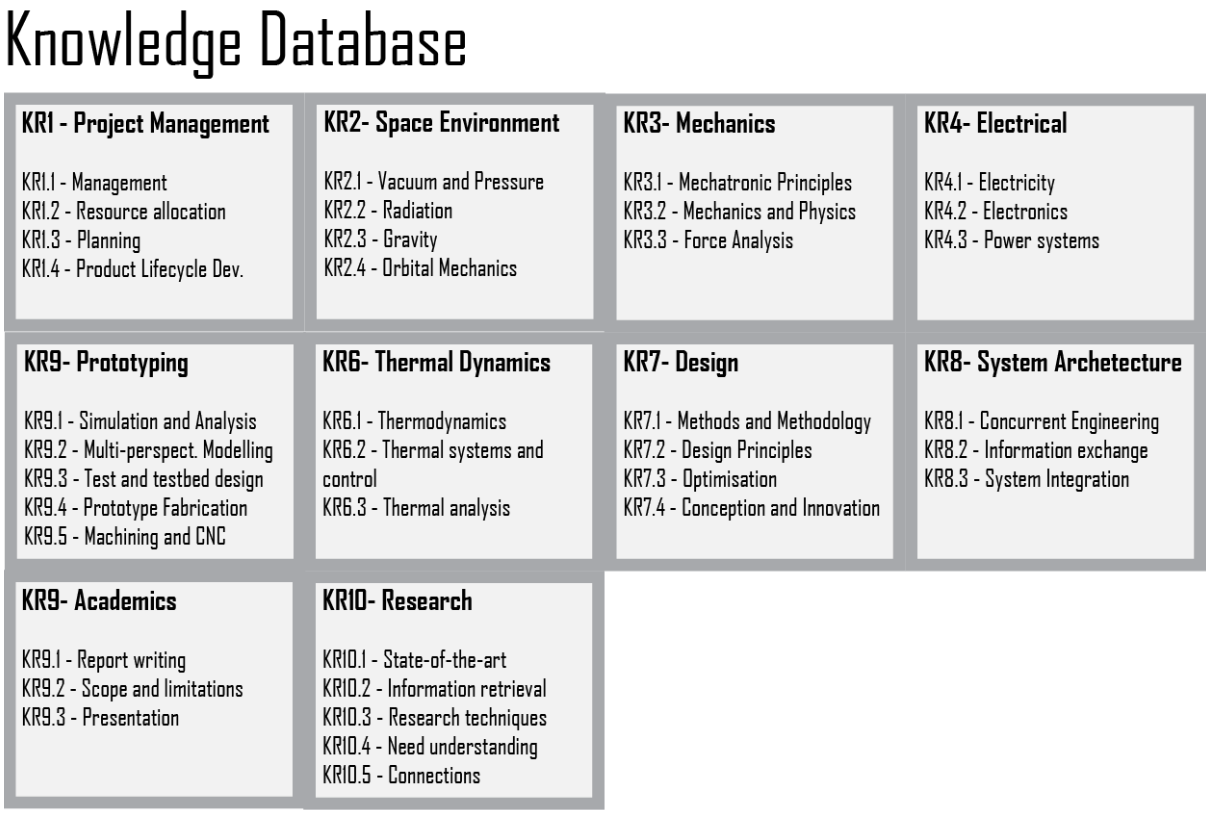


Figure 6-4 - Tiv-Model's high-level applied to the interface project (older variant)

The later stages of the model were omitted as there was no need for the manufacture of the product. The research was purely academic; thus, the write-ups were included in review reports. The Legislative stage was also removed as there was no client nor were the participants designing to a specific regulatory standard at this point. Contextual and environmental information was gathered as part of the background research task.

Knowledge databases

Knowledge databases were generated based on previous experience with similar academic projects and the complete list is shown in Figure 6-5.



Knowledge Database

KR1 - Project Management
KR1.1 - Management
KR1.2 - Resource allocation
KR1.3 - Planning
KR1.4 - Product Lifecycle Dev.

KR2- Space Environment
KR2.1 - Vacuum and Pressure
KR2.2 - Radiation
KR2.3 - Gravity
KR2.4 - Orbital Mechanics

KR3- Mechanics
KR3.1 - Mechatronic Principles
KR3.2 - Mechanics and Physics
KR3.3 - Force Analysis

KR4- Electrical
KR4.1 - Electricity
KR4.2 - Electronics
KR4.3 - Power systems

KR9- Prototyping
KR9.1 - Simulation and Analysis
KR9.2 - Multi-perspect. Modelling
KR9.3 - Test and testbed design
KR9.4 - Prototype Fabrication
KR9.5 - Machining and CNC

KR6- Thermal Dynamics
KR6.1 - Thermodynamics
KR6.2 - Thermal systems and control
KR6.3 - Thermal analysis

KR7- Design
KR7.1 - Methods and Methodology
KR7.2 - Design Principles
KR7.3 - Optimisation
KR7.4 - Conception and Innovation

KR8- System Archetecture
KR8.1 - Concurrent Engineering
KR8.2 - Information exchange
KR8.3 - System Integration

KR9- Academics
KR9.1 - Report writing
KR9.2 - Scope and limitations
KR9.3 - Presentation

KR10- Research
KR10.1 - State-of-the-art
KR10.2 - Information retrieval
KR10.3 - Research techniques
KR10.4 - Need understanding
KR10.5 - Connections

Figure 6-5 - Knowledge databases for case study (older variant)

These were the Domains identified for use in the research project, all relevant skills and engineering domains were captured in this diagram. In a typical project, these would be used to tag tasks, personnel, and other elements so that project management could utilise that information.

Mid-level Work packages

Creation of the mid-level work packages would be critical to communicating the detail work to the design team and others involved with the project. This case study was carried out alone, so the communicative aspect was null here. Key tasks were planned to demonstrate how this should be carried out in a hypothetical team-based environment. Several critical tasks were selected for the project, spread across various stages to show diversity of application. Existing design research, creation of requirements and initial conceptual design were the three relevant components of the design project, and thus these were planned to demonstrate the process.

WP Name	**Existing design research**	
Task	Background research	
Aim	**Method/s**	**Deliverable**
To establish a current “State-of-the-art” with regards to existing interface technology	Benchmarking, literature review	Report – Existing interface tech

Procedure

Check sources for information regarding state-of-the-art in several aspects;

- Connection interfacing
- Thermal transfer
- Power transfer
- Data transfer
- Modular spacecraft

Internet sources

- Google/Scholar
- SUPrimo
- NASA/ESA/other space organisation sites

Physical sources

- Library books
- University paper collection#

Expert sources

- University researchers/staff
- Industry connections

Report format does not need to follow template, should contain abstract and summary

Knowledge Database	D1-4,6,8-10 (D10 is key)

WP Name	**Creation of requirements**	
Task	Initial specifications/planning	
Aim	**Method/s**	**Deliverable**
Create the initial requirements document using qualitative statements	Pugh's PDS elements - modified	Requirements document - Rough
Procedure		
Using Pugh's PDS elements, modified for the context of the situation, develop a series of broad requirements that the interface should satisfy. Requirements should be open ended and qualitative. The document should read like a numbered item list, with each heading expanded upon in its description.		
Knowledge Database	D2-4,6-8 (D8 is key)	

In the hypothetical scenario, once the work packages are complete for the coming tasks, the project will develop the preliminary requirements document. This is a deliverable that is linked to a milestone review, outlined in orange in the macro-level. This review, the PRR, checks that the initial work package is complete, consisting of the background research, the project planning, and initial requirements development. In this case, the workload was rather light, but in a more serious commercial project there would be many more items to check. The review can be reflective in nature in a solo project, presentable to a supervisor in this situation as opposed to a board consisting of design and client organisation members. Once this review was passed, the workload of the project began in the next stage.

Qualitative

The Qualitative stage consists mostly of the conceptual design components of the project and thus takes most of the creative energy. Ultimately, there was not much to demonstrate for this case study within this stage. However, it helped to show the logic behind the work package at this stage. Using the work package for “Initial conceptual design”, below, the nature and instructions for the work package were determined.

WP Name	**Initial conceptual design**	
Task	Conceptual design	
Aim	**Method/s**	**Deliverable**
Provide series of initial concepts broken down by function	Brainstorming, TRIZ, 6-3-5	Initial concepts
Procedure		

Using traditional design methods, develop a series of rough designs for each of these sub-functions:

- Connection
- Thermal
- Data
- Power
- Physical attributes
- Other

Using Brainstorming, come up with these categories and any additional information required.
Using 6-3-6, generate additional concepts, slightly more refined in quality
Using TRIZ, refine these concepts further.
In each stage, group together concepts that are the same or too similar.
Place these concepts in a presentable sketch format if possible.

Knowledge Database	D2-4,6-8 (D7 is key)

The title of this WP and the task it belongs to are shown so that the concept and timing of the work may be communicated.

Aim

Provides the user with goal-based context to the work. The user knows that the aim is to provide conceptual solutions to each functional problem.

Methods

These were specified in this case study; however, they can be left unspecified and to the behest of the user.

Deliverable

This is the expected outcome of the task so that the user knows the expected outcome of the work.

Protocol

The user is given a short rundown of the expected work and output format. This is essential in communicating the work to a novice but is considered only a part of the teaching process. To a design veteran this is ultimately a reference component that contextualises the objective.

From this, the designers tasked with the initial concept design subtask would know their objective, the context behind it and some means of achieving the goal. With these ingredients it was ensured that time spent pondering the task was at a minimum and any questions would be answered by the work package. Explaining the task in detail like this created confidence in the designer’s ability to understand what is expected of them, improving lead times and quality.

Quantitative

The Quantitative stage encompassed all the detail design work and some more structured forms of prototyping. In this stage, the project was continued in its development. The examples demonstrated in this section were the resolution of two issues that came up in the first prototype model of the design using C-QuARK.

The design prototype, pictured in Figure 6-6, was physically, thermally, and electronically functional when plugged into compatible hardware. Testing the data and power transfer was a simple task, however testing complex aspects, such as mating force, required the use of sensors. The problem with this, however, was that the design’s connecting interfaces left no room for any reasonably sized pressure sensors in between. C-QuARK was used to generate solutions to this problem.

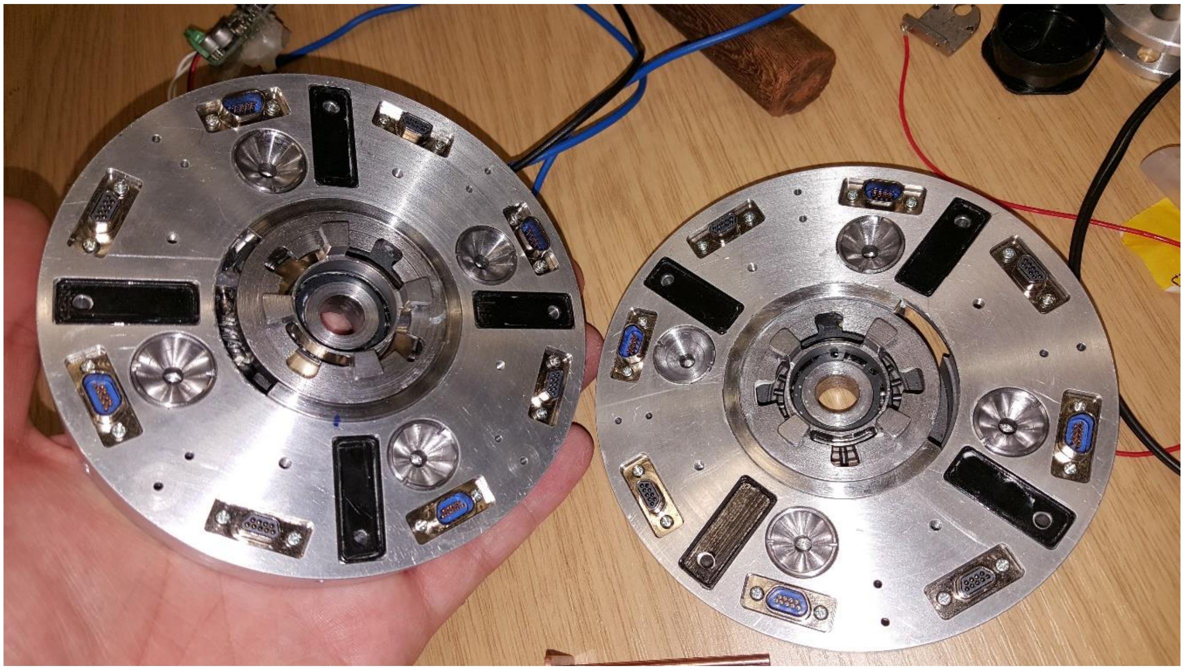


Figure 6-6 - Academic spacecraft interface

It started by selecting one of the strategies from the grid, in this case picking "Consider issues" was an effective starting point. Then, the designer moves between strategies following the arrows (or as one sees fit if it is thought to bring a clearer answer).

Consider issues: The sensors used to measure connection pressure do not fit with the design.

Aware of reason: The sensors are too big, or the design is too tight.

Aware of limitations: Sensors are not manufactured any thinner, at least not for a reasonable cost. The prototype interface is mostly machined aluminium but can be re-machined.

Aware of trade-offs: Purchasing/designing and manufacturing new sensor probably unrealistic and outside of the scope of the project. Modifying prototype to accommodate sensors is quicker, cheaper and in scope, but may compromise parts of prototype.

Question pursuing: Is the sensor data required? It will increase robustness if gathered.

From this the final decision was made, the prototype could be re-machined at a low cost to incorporate the integration of the pressure sensor already present at the lab. This required a few hours to create and communicate the detail drawings of the new cut and a suitable time slot to be found for performing the action in the workshop. The sensor integration helps provide valuable data for communicating the effectiveness of the design, and the contact pressure was important information for engineers to work with.

The second instance of using C-QuARK was on a design flaw encountered during the initial prototyping. The roto-locking mechanism was actuated into place by a servo, guided by a rod that pulls the locking mechanism back into the interface after mating to increase contact pressure. This feature is shown in Figure 6-7.

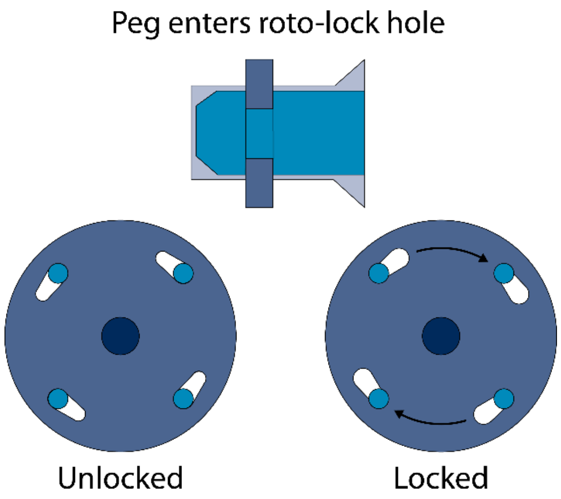


Figure 6-7 - Roto-lock single rod guide

The issue was that the roto-lock had a lot of back-and-forward axial movement that means that the lock was too loose when connecting to the other interface. This limited the adjustment of the contact pressure, resulting in an unreliable connection. C-QuARK was used to get to the source of the problem and determine a solution. The first step was to bring awareness of the reason for this looseness.

Aware of reason: The rod on the rotational lock was very loose within the guiding frame, thus the play in the interface was too great. Also, having one contact point caused the roto-lock to rotate around that point, adding further instability and weakness to the design.

Refer to past designs: Looking at previous research there were similar designs for these elements that have rods guided by other interference pieces. These designs tended to have 3-4 rods arranged evenly around a circle to balance the design out. The designs also showed that the tolerance of the fit between the rods and the guiding pieces were quite tight, ~+100um.

Consider issues: Prototype redesign of this scale had some cost association; new components must be machined.

Keep options open: There was time to consider other options until the next prototype run. A new design could be in order.

Using C-QuARK, the cause, and potential solutions to one of the mating problems was revealed. No changes were actioned at that moment, but one could opt to consider the issue further in another design pass-through. This was a decent choice as the potential impact from this design change would have been worthy of a more in-depth redesign, and not subject to a “quick fix”.

Evaluative

In the Evaluative stage (now replaced with the Amalgamative stage), more detailed methods of evaluation of the design were employed considering environmental aspects. In an ideal situation this simulation is done in a comprehensive testbed environment. Unfortunately, due to the extreme space environments this usually cannot be fully accomplished. Many components are instead tested across several physical platforms. This is expensive, and in an academic environment especially this cost is outside of the remit of the project. For this reason, knowing that the space environment cannot be recreated here, Multi-perspective modelling was used. Multi-perspective modelling is performed as one simulation from multiple perspectives, i.e., a simulation or analysis run that considers thermal, mechanical and electrical loads as well as any other performance expectations, running at the same time. This is not always feasible to perform, either by limitations of CAD package, time, or other resource. Thus, the alternative of a combinatorial view of analyses is also feasible. The principle is to look at all situatable aspects of a critical piece of hardware or product and consider the effects of each on the other. For this academic project the following simulations were considered:

- Mechanical static load
- Mechanical dynamic load
- Environmental thermal load
- Active thermal load
- Electrical thermal load

A commercial project may consider more factors; however, these are all within the scope of a hypothetical academic design. It must be understood that each of these types of loads will have some effect on the other; small but significant. When the simulations are performed in the form of CAD based FEA, the effect that each load will have on the analysis should be considered. If not computable within the CAD package, then a FoS adjustment may be required.

Case study conclusion

From this case study some observations could be made:

- The Tiv-Model can work in the context of the example problems given
    - Only one example of this is available at this time, but no major adjustments were made outside of the scope of the model to fit the problem.
- A supporting series of documentation would be a useful set of tools for the user
    - When working on the planning, a reference document would have been useful for a layman or someone not well versed with the model.
- The modularity of the methodology is useful, especially in academic projects
    - This modularity was extended to the Mid-level.
- Multi-perspective modelling is difficult to apply in a small scope project
    - The importance of multi-perspective modelling in teaching material was further emphasised in Phase 1. It was understood that for small scale projects this function adds little value. Multi-perspective modelling takes a back seat to a much more reasonable basic virtual prototype. It was understood that this was a multi-

disciplinary task with a huge amount of work required to function correctly, so no expectations were made for a complete multi-perspective model.

The first case study shows that the model is viable, it performs the actions expected of it within the context assigned to it. The case study serves as a suitable reality check and is more than enough to confirm the Empirical Performance Validity with regards to the V-Square. With that, the 4th goal of the V-Square method has been proven. The next step was to prove the 5th goal through a series of comparative studies.

6.3.2 Student studies - Phase 1

The first phase of the statistical analysis study acted as a testbed for the study itself. This phase was performed not only as a means of supplying data but also to ensure that the study was working as intended. Students learned both V-Model and Tiv-Model and choose the one they wished to work with. This resulted in two groups choosing Tiv-Model and 4 groups choosing V-Model. This did not affect the quality of the data in the end but suggested that the students may have preferred using something tried-and-tested rather than something novel.

Reading the results

The p-value in these t-tests represented the probability that the null hypothesis was correct; the smaller the p-value, the more confidently the null hypothesis could be rejected. P-values under 0.1 were considered as a rejection of the null hypothesis, with increasing levels of confidence for values under 0.05 and 0.01. If the p-value was not less than 0.1, then there was not enough significant evidence to fully reject the null hypothesis and thus it must be accepted. Table 6-8, shows the results from phase 1. To read the table, a key is provided below.

Null Hyp?	Was the null hypothesis rejected? Which confidence interval?	**SA**	Strongly Agree
Model	Model results	**A**	Agree
N	Number of participants	**NS**	Not Sure
m	Mean agreeableness	**D**	Disagree
σ	Standard deviation	**SD**	Strongly Disagree
p	P-value, likihood of null hyp.	**Fav**	Favoured model

Table 6-7 - Tiv-Model comparative study table key

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
1	*V*	0	0	1	6	1	8	-1	0.534522484	0.063952827	Reject, 0.1	V
	Tiv	0	2	2	4	0	8	-0.25	0.88640526			
2	*V*	1	0	0	5	2	8	-0.875	1.246423455	0.838826695	Accept Null	V
	Tiv	0	2	0	4	2	8	-0.75	1.164964745			
3	*V*	2	4	1	0	1	8	0.75	1.281739889	0.294799162	Accept Null	V
	Tiv	0	4	1	3	0	8	0.125	0.991031209			
4	*V*	1	5	1	0	1	8	0.625	1.187734939	0.402137006	Accept Null	V
	Tiv	1	2	2	3	0	8	0.125	1.125991626			
5	*V*	3	3	0	0	2	8	0.625	1.685018016	0.484084619	Accept Null	Tiv
	Tiv	3	4	0	1	0	8	1.125	0.991031209			
6	*V*	1	3	3	1	0	8	0.5	0.9258201	0.227251719	Accept Null	V
	Tiv	0	4	1	3	0	8	0.125	0.991031209			
7	*V*	1	0	3	3	1	8	-0.375	1.187734939	0.227251719	Accept Null	V
	Tiv	1	3	3	0	1	8	0.375	1.187734939			
8	*V*	0	3	3	1	1	8	0	1.069044968	0.430697441	Accept Null	Tiv
	Tiv	0	4	3	1	0	8	0.375	0.744023809			
9	*V*	1	0	0	6	1	8	-0.75	1.164964745	1	Accept Null	NA
	Tiv	0	1	1	5	1	8	-0.75	0.88640526			
10	*V*	0	2	1	4	1	8	-0.5	1.069044968	0.417389114	Accept Null	V
	Tiv	1	2	2	2	1	8	0	1.309307341			
11	*V*	1	0	1	6	0	8	-0.5	1.069044968	0.478914445	Accept Null	V
	Tiv	0	3	1	4	0	8	-0.125	0.991031209			
12	*V*	1	0	0	5	2	8	-0.875	1.246423455	0.481361601	Accept Null	V
	Tiv	0	1	2	5	0	8	-0.5	0.755928946			
13	*V*	0	7	0	0	1	8	0.625	1.060660172	0.814905845	Accept Null	Tiv
	Tiv	2	3	2	1	0	8	0.75	1.035098339			

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
14	*V*	0	2	2	3	1	8	-0.375	1.060660172	0.654118589	Accept Null	Tiv
	Tiv	0	2	2	3	0	7	-0.143	0.899735411			
15	*V*	2	4	1	0	1	8	0.75	1.281739889	0.405760988	Accept Null	V
	Tiv	0	5	0	3	0	8	0.25	1.035098339			
16	*V*	0	6	0	1	1	8	0.375	1.187734939	0.709220098	Accept Null	Tiv
	Tiv	0	5	1	1	0	7	0.571	0.786795792			
17	*V*	0	5	1	1	1	8	0.25	1.164964745	0.177002219	Accept Null	V
	Tiv	0	1	3	3	1	8	-0.5	0.9258201			
18	*V*	1	0	0	6	1	8	-0.75	1.164964745	0.405131505	Accept Null	V
	Tiv	0	3	1	3	1	8	-0.25	1.164964745			
19	*V*	0	7	0	0	1	8	0.625	1.060660172	0.805432793	Accept Null	V
	Tiv	0	6	0	2	0	8	0.5	0.9258201			
20	*V*	1	4	1	1	1	8	0.375	1.302470181	1	Accept Null	NA
	Tiv	1	3	3	0	1	8	0.375	1.187734939			

Table 6-8 - Tiv-Model comparative study phase 1 results

Question 1 - Overall, I found the methodology difficult to use

The first observation of this question bore a fruitful result; the difference between the Tiv-Model and V-Model in terms of student agreeableness was visible. More students felt that Tiv-Model was difficult to use compared to those who used V-Model.

The null hypothesis could be rejected with some small confidence and acceptance of errors, Tiv-Model in this instance appeared more difficult to use.

Question 2 - I would definitely NOT use this model to develop mechatronic systems

The data on this question is fairly spread, students were certain about their feelings regarding re-use of their chosen methodology. Overall, V-Model users had a lower average agreeableness, but not significantly so. Users tended to disagree with the statement, although a small number of outliers agreed; the opinions were somewhat individualistic in this sense. The null hypothesis must be accepted with these numbers.

Question 3 - *I would use this model instead of Pugh's TDM if I have to develop a mechatronic system*

V-Model users had a higher average agreeableness but also a much higher deviation than that of Tiv-Model user opinions with regards to this statement. The differences are not significant enough to merit rejection of the null hypothesis however, and thus it was assumed that students would prefer either methodology in this situation.

Question 4 - *I found the rules of the model clear and easy to understand*

Users of the V-Model were, on average, in agreement with the statement that the rules of the model were clear and easy to understand. Tiv-Model users were somewhat uncertain, their answers varied. The statistical difference was not significant enough to reject the null hypothesis.

Question 5 - *I found that the model was suitable for this kind of project*

For those students who agreed with the statement, both methodology’s users had a balanced spread. However, for those who disagreed with the statement, the V-Model users felt the strongest. Users were certain of their feelings with this question and despite the higher agreeableness average from Tiv-Model users, assumptions could not be made based on this sample.

Question 6 - *I found that my existing knowledge worked well with the model*

Users of both methodologies averaged around uncertainty when deciding if their existing knowledge was useful when dealing with the Tiv-Model and V-Model. Some speculative observations could be made from this question, as the intent was to frame the use of these methodologies within the context of the previous student experience. The null hypothesis is accepted but the question also delivered important feedback.

Question 7 - *I found that I was limited to specific means or methods in order to achieve my goal*

Interestingly, the results of this quiz were flipped across the model split. Tiv-Model users agreed more that their options for methods were limited as opposed to the V-Model users. Not statistically significant enough for rejecting any hypotheses, but actionable feedback overall.

Question 8 - *I believe that the model would reduce the effort required to produce mechatronic systems*

Across both models there was uncertainty regarding this statement. It appeared that half of the students were uncertain if their chosen methodology would reduce effort for the design of mechatronic systems. This could be due to the framing of the question, or the students lacking a frame of reference. In this phase there were a sizable number of students who had not undertaken a design project prior to this one, which could contribute to the answer. Alternatively, they could deem that the methodology was neither more demanding nor less demanding than their idea of other methodologies. Assumptions could not be drawn from this data, as it was not statistically significant.

Question 9 - *Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems*

Both sets of students generally disagreed with the statement that their methodology did not provide an effective solution to their design problem. Although both averages were the same, the V-Model group deviated more. The tilt to disagreement from uncertainty was slight and statistically insignificant, but it was useful to see that there was a general tendency towards agreement.

Question 10 - *I am NOT confident about applying this method in practice*

There was little difference in the results between V-Model users and Tiv-Model users. Although V-Model users were slightly more disagreeable with the statement and less variable, the results were not statistically significant.

Question 11 - *I found it difficult to apply the model to the project*

Users of the V-Model were generally in disagreement with the above statement, whereas the Tiv-Model users were split and averaged around uncertainty. The statistics were insignificant, however.

Question 12 - *Using this model would make it more difficult to complete mechatronic projects*

V-Model student results were somewhat spread by comparison of Tiv-Model, and their average was lower in agreeableness. Tiv-Model user's uncertainty was more pronounced, but the results were statistically insignificant, however.

Question 13 - *This model would make it easier for designers to produce mechatronic systems*

V-Model users were consistent with their agreeableness on the ease of use of their model, while Tiv-Model users are spread around agreement. An outlier lowers the average for V-Model, but both remain similarly positive. Results were statistically insignificant.

Question 14 - *Using this model would make it easier to communicate concepts in a mechatronic project*

A result was missing from the Tiv-Model sample due to one of the participants accidentally missing the question. Both groups displayed almost identical results.

Question 15 - *I found the model easy to learn*

V-Model results were well spread and of a higher average than the results from the Tiv-Model group. Despite this, results were still statistically insignificant.

Question 16 - *Overall, the model's information was well presented*

The results suggested that the two models were similarly received on how they were presented, Tiv-Model's average was presented as slightly higher but not significantly.

Question 17 - *I would use this model again in a general product development project*

The differences in the averages were sizable. V-Model users were between uncertainty and agreement about using the model again. Tiv-Model users were between uncertainty and disagreement, with high variances. Statistics were close to giving confidence in rejection but not quite, however they did give insight on potential areas of improvement for Tiv-Model.

Question 18 - *I found the model complex and difficult to follow*

The variance was similar across the two groups, but V-Model users strongly disagreed more than the Tiv-Model users on average. The null hypothesis was accepted.

Question 19 - *Overall, I found the model to be useful*

Again, both results were very close in nature, with V-Model users just inching out higher average agreeability over Tiv-Model users.

Question 20 - *Overall, I found that the model freely allowed me to make design decisions*

The results were well spread across each of the groups, averaging the same, there was no reason to reject the null hypothesis.

Summary

Using the surveys as a form of feedback, several improvements were made to the Tiv-Model to raise its standing amongst students. The goal was to verify and validate the model by benchmarking against an industry standard model. This case study iteration was used as an opportunity to make improvements to the methodology, the outcomes of which are discussed in the next section. Some weak points in the Tiv-Model were noted and adjusted accordingly. Figure 6-8 shows the results for phase 1, 1 survey question showed favourable results for V-Model, the rest were inconclusive.

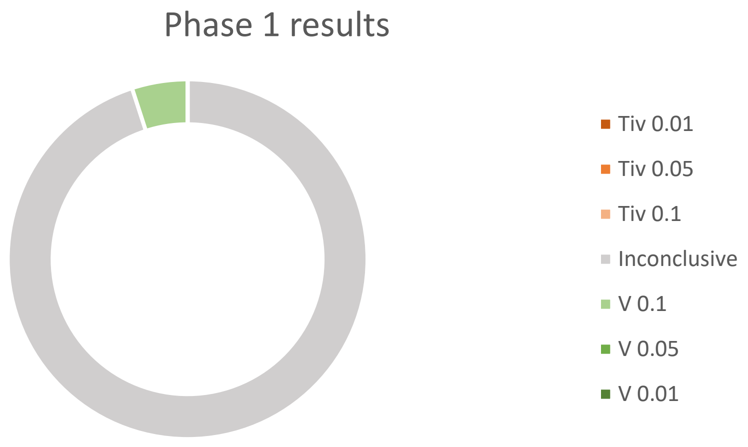


Figure 6-8 - Phase 1 hypothesis rejections

The Tiv-Model was perceived as slightly less usable, clear, and simple as V-Model. Thus, some minor changes were made to the Tiv-Model to appeal to the student's needs for the project. Visual changes were made, and terminology was revisited to work with the student's needs. In addition, the entire teaching package was reworked. The presentation was readjusted, new detailed handouts were created, and the methodology workshop was prepared, ready for phase 2.

6.3.3 Student studies - Phase 2

Phase 2's test procedure started similarly to phase 1, however, there were adjustments made due to feedback to mitigate some issues. General improvements to the overall experience were made for the students. Changes were made to both the teaching elements and the Tiv-Model. Two new handouts were created for the students. One document acted as an anatomical breakdown outlining the theory behind the V-Model and the Tiv-Model, and the other acted as an instruction manual for setup and use. Explanations and details were covered during the presentation portion of the teaching component, as it was desirable for students to engage with the models on a much deeper level. The workshop session was introduced as a hands-on experience for setting up the model. An example problem was run through and a high-level creative process was used to solve it involving the use of the student's chosen model, which was now manually assigned to each group. One of the most significant changes in the teaching and experiment environments was the division of each model into macro, mid and micro-level. This perceptive boundary was presented across both methodologies to ensure equal understanding. This let the students learn in a simplified manner and allowed comparative data to be drawn. Three more questions were introduced into the survey covered in the end of this section; the data is shown below in Table 6-9.

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
1	*V*	0	5	6	23	2	36	-0.611	0.802772972	0.102726178	Accept Null	V
	Tiv	1	13	0	19	2	35	-0.229	1.113703791			
2	*V*	0	0	8	22	6	36	-0.944	0.629940788	0.176924224	Accept Null	V
	Tiv	0	5	7	17	6	35	-0.686	0.932152114			
3	*V*	2	10	13	8	3	36	0	1.041976145	0.021427603	Reject, 0.05	Tiv
	Tiv	2	18	11	4	0	35	0.514	0.781078763			

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
4	*V*	4	24	1	6	1	36	0.667	0.985610761	0.602947817	Accept Null	V
	Tiv	4	20	2	9	0	35	0.543	1.010033696			
5	*V*	6	24	4	1	1	36	0.917	0.806225775	0.885932715	Accept Null	Tiv
	Tiv	6	23	4	2	0	35	0.943	0.725293334			
6	*V*	3	21	4	7	1	36	0.5	1	0.373843103	Accept Null	Tiv
	Tiv	7	17	6	4	1	35	0.714	1.016667815			
7	*V*	1	11	9	13	2	36	-0.111	1.007905261	0.348595423	Accept Null	Tiv
	Tiv	0	7	10	18	0	35	-0.314	0.795998395			
8	*V*	1	21	7	5	2	36	0.389	0.96444737	0.318449033	Accept Null	V
	Tiv	1	12	15	6	1	35	0.171	0.85700279			
9	*V*	1	2	4	21	8	36	-0.917	0.906326967	0.257566503	Accept Null	V
	Tiv	0	4	6	22	3	35	-0.686	0.795998395			
10	*V*	2	12	1	17	4	36	-0.25	1.204159458	0.720983938	Accept Null	V
	Tiv	6	5	6	14	4	35	-0.143	1.309307341			
11	*V*	1	7	6	20	2	36	-0.417	0.967323258	0.596402433	Accept Null	V
	Tiv	2	9	3	19	2	35	-0.286	1.100038196			
12	*V*	0	1	10	22	3	36	-0.75	0.649175301	0.594300877	Accept Null	V
	Tiv	0	4	7	21	3	35	-0.657	0.802307596			
13	*V*	1	21	10	3	1	36	0.5	0.810643483	0.514848148	Accept Null	Tiv
	Tiv	4	18	9	4	0	35	0.629	0.843163311			
14	*V*	3	14	10	7	1	35	0.314	0.99325456	0.789798793	Accept Null	V
	Tiv	0	16	12	7	0	35	0.257	0.780002155			
15	*V*	5	14	3	11	3	36	0.194	1.260826134	0.60240634	Accept Null	V
	Tiv	5	13	1	10	6	35	0.029	1.403477075			
16	*V*	5	23	3	5	0	36	0.778	0.865567068	0.057492122	Reject, 0.1	V
	Tiv	1	23	0	8	3	35	0.314	1.131667915			

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
17	*V*	1	12	11	7	5	36	-0.083	1.105182596	0.654098322	Accept Null	V
	Tiv	0	11	12	6	6	35	-0.2	1.079215401			
18	*V*	0	9	2	20	5	36	-0.583	1.024695077	0.04024368	Reject, 0.05	V
	Tiv	5	8	4	17	1	35	-0.029	1.200140048			
19	*V*	6	18	8	4	0	36	0.722	0.881917104	0.568398869	Accept Null	V
	Tiv	3	22	3	7	0	35	0.6	0.913944264			
20	*V*	1	19	8	7	1	36	0.333	0.9258201	0.826096595	Accept Null	V
	Tiv	2	14	11	8	0	35	0.286	0.893487173			
21	*V*	5	15	13	3	0	36	0.611	0.837608084	0.21675244	Accept Null	Tiv
	Tiv	3	24	7	1	0	35	0.829	0.617667067			
22	*V*	1	14	15	5	1	36	0.25	0.840917866	0.395720437	Accept Null	Tiv
	Tiv	2	18	9	5	1	35	0.429	0.916698497			
23	*V*	0	21	11	3	1	36	0.444	0.772544754	0.127077693	Accept Null	Tiv
	Tiv	5	19	9	1	1	35	0.743	0.852085923			

Table 6-9 - Tiv-Model comparative study phase 2 results

Question 1 - *Overall, I found the methodology difficult to use*

Compared to the first phase, question 1’s results showed a slight increase in agreeableness for the question statement in V-Model, with variances increasing across the board. Again, it appeared as though Tiv-Model users were somewhat more dissatisfied compared to V-Model users. The null hypothesis was accepted, but barely. Actions were taken to mitigate usability based on the feedback from this question.

Question 2 - *I would definitely NOT use this model to develop mechatronic systems*

V-Model user agreeableness dropped slightly, and Tiv-Model user agreeableness increased. Although this showed a small part in satisfaction it did not justify a hypothesis rejection.

Question 3 - *I would use this model instead of Pugh's TDM if I have to develop a mechatronic system*

Here, the opposite trend from question 2 was visible; Tiv-Model user agreeableness increased in a positive line of questioning and decreased in V-Model. It appeared that users of the Tiv-Model were somewhat more inclined to use the methodology again compared to users of the V-Model.

The null hypothesis was rejected with some confidence. It appeared that users of the Tiv-Model understood that the model is specifically designed for high complexity projects and that the Pugh TDM cannot cope with the kinds of work specialised in mechatronics. V-Model users possibly did not make this distinction due to the similarities that it has with Pugh’s, and the variable nature of V-Model depictions in general.

Question 4 - *I found the rules of the model clear and easy to understand*

On V-Model’s side there was very little change in perception of rule clarity, however changes made to the Tiv-Model could be accountable for the slight increase in agreeability from this group. Findings were suggestive but not statistically significant.

Question 5 - *I found that the model was suitable for this kind of project*

V-Model agreeableness had increased somewhat whereas Tiv-Model agreeableness had decreased slightly, and variances were lower. This small change from phase 1 could be attributed to changes made in the teaching plan. The aim was to teach V-Model and Tiv-Model in an identical fashion and leave inferences of suitability to the students.

Question 6 - *I found that my existing knowledge worked well with the model*

The aim was to tailor the learning experience and frame it in a manner that draws on the prior knowledge of the students. However, other factors in the teaching changes may have contributed to a decrease in agreeableness in the Tiv-Model students. With the increased depth the knowledge was presented with, there was an increase in complexity. Principles were visited that were not well explored for the design students with their previous methodologies, such as management and understanding of design complexity. So, while information was contextualised to the undergraduate’s needs, there was additional unfamiliar information, specifically in Tiv-

Model. This could be an explanation for the decrease in Tiv-Model agreeableness, but not V-Model.

Question 7 - *I found that I was limited to specific means or methods in order to achieve my goal*

The changes made to Tiv-Model had demonstrated a moderate decrease in agreeableness for this statement. Users now appeared to feel less limited by the methodology than the previous phase for Tiv-Model, with very little change on the V-Model side.

Question 8 - *I believe that the model would reduce the effort required to produce mechatronic systems*

It could be argued that the students seen the methodologies as more complex than before. Perhaps Tiv-Model’s complexities outweighed the V-Models from experience. If this was true, then this could be used to explain the small switch in numbers, with Tiv-Model users less agreeable than before and V-Model students more agreeable. Alternatively, and perhaps more likely, the increased sample size could account for this minor change. Statistics were still not significant enough.

Question 9 - *Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems*

The biggest change in data between the two phases was the p-value, which dropped by around 0.75. This was likely brought about by a move to more concrete data from the large population size. It could be seen that while V-Model users were more spread on the issue, Tiv-Model users were less unanimous in their disagreement with the statement.

Question 10 - *I am NOT confident about applying this method in practice*

There were only minor changes in the confidence of students in applying the methodology. This could be attributed, again, to the introduction of more in-depth information, combined with the equalising factor of the re-contextualisation of that information. No solid assumptions could be made with the data, but this was noted as feedback for another phase.

Question 11 - *I found it difficult to apply the model to the project*

There was not much change between both phases; Tiv-Model agreeableness lowered slightly. The teaching changes and explanations made little to no difference in the confidence of students for applying the model to their project.

Question 12 - *Using this model would make it more difficult to complete mechatronic projects*

There was a small decrease in agreeableness with Tiv-Model users and an equally tiny increase with V-Model users, although neither observation is statistically significant.

Question 13 - *This model would make it easier for designers to produce mechatronic systems*

Compared to the previous phase, variances had shrunk, and agreeableness had decreased slightly across the board for this statement, again possibly due to the teaching changes discussed. No solid observations could be made otherwise.

Question 14 - *Using this model would make it easier to communicate concepts in a mechatronic project*

Interestingly, the disagreement of the students in the previous phase had switched to agreement. Students now found that the models helped communication of concepts easier than before, in general. This could be attributed to the Mid-level concepts taught to the students regarding documentation.

Question 15 - *I found the model easy to learn*

Not dissimilarly from the previous phase, there was a wide range of opinions on the ease of learning. Overall, the student’s agreeableness had been reduced between phases and variances have been increased. Again, this could be attributed to the information presented in teaching changes. The null hypothesis is accepted, but notes are taken for feedback and to improve the learnability of these models.

Question 16 - *Overall, the model's information was well presented*

Contrary to the observations made in the previous questions regarding how the content was presented and the learnability of the two methodologies, there was a surprising result in question 16. The V-Model students were much more agreeable that the statement declaring that information was presented well for their model compared to the Tiv-Model group. The information subdivisions for Tiv-Model likely added needless complexity into the teaching environment. Improvements could be made to both the teaching process and Tiv-Model from this question.

The null hypothesis was rejected and it was concluded that, with a little confidence, that V-Model was well presented comparatively to Tiv-Model.

Question 17 - *I would use this model again in a general product development project*

Again, following on previous observations, Tiv-Model suffered a loss in agreeableness with regards to perceived effort required for use, whilst V-Model did not suffer too much from the teaching changes. In this instance it may be attributed to larger population size.

Question 18 - *I found the model complex and difficult to follow*

A slight increase in agreeableness seen from both model user groups again, in line with the observations of previous questions. This time, however, Tiv-Model users were more confident in their feelings and some strongly agree that the model was too complex. This was noted as feedback for improving the model.

Additionally, it may also be concluded that the findings could point towards V-Model being less complex and easier to follow than Tiv-Model.

Question 19 - *Overall, I found the model to be useful*

Whilst previous observations have been negative regarding the student’s perceptions of efficiency, their opinion on the effectiveness of the Tiv-Model was promising. Students showed an increased agreeableness regarding both model’s usefulness, although this error margin was partly accountable from increased sample size also.

Question 20 - *Overall, I found that the model freely allowed me to make design decisions*

The observations regarding freedom for both models remained relatively unchanged across the two phases thus far. This signalled that more could be done to emphasise initiative driven decisions by the users within the core of the methodology.

Question 21 - *The Macro-level model was useful for this project*

A measure of the students perceived usefulness of the overall macro-model was desirable. The students were questioned about the primary visual element of the methodology and its overall ethos. Students using Tiv-Model tended to be more agreeable with this statement than those with V-Model, although statistical insignificance does not allow conclusions on that point.

Question 22 - *The Micro-level problem solving technique was useful for this project*

This question helped gain understanding of the usefulness of the inclusion of the Micro-level in both design methodologies. Understandably, there was a large amount of uncertainty with this component. It could be assumed that many of the students did not get a viable opportunity to use this part at all, although the V-Model micro-level had a much wider applicability to problem scenarios.

Question 23 - *The Mid-level task management was useful for this project*

The Mid-level component of the methodology was thought to be a net positive in terms of usefulness as students were encouraged to spend a lot of time utilising it in documentation and planning. However, some students were notably inconvenienced by this. A limitation in the project assignment was that the example problem was not large enough to merit some of the effort put into documentation as it would be in a complex system project. It could be accepted that, in this scenario, the students would not find the mid-level components to be as useful as they could be.

Summary

Moving from the previous phase to this one, the intention was to make improvements to the teaching process, Tiv-Model and the experiment setup. Credible results, an improved student learning experience and optimised Tiv-Model were all desirable outcomes. The ideal was that a teaching presence would be used to introduce design methodologies into the classroom environment. The expectation was that this would be of benefit to the students in their studies, not just to these experiments. The iterative feedback loop could also be used to make improvements to the Tiv-Model. The resulting robustness was purely of benefit to the thesis and for the confidence of those who base any further observations on it. Figure 6-9 shows the results of this phase, 2 questions showed favourable results for Tiv-Model and 1 question for V-Model. The remainder were inconclusive.

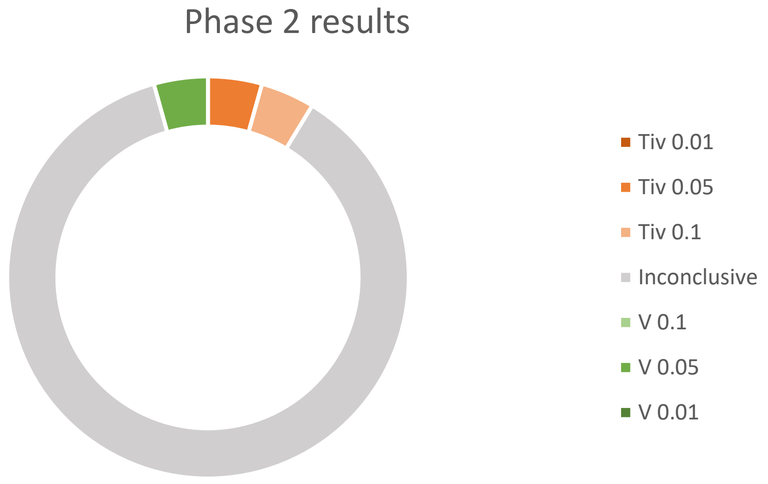


Figure 6-9 - Phase 2 hypothesis rejections

Some primary observations were noted throughout the phase;

- Tiv-Model users seemed more likely to use the methodology again in a similar project.
- More V-Model users felt that the information presented within the model was presented well compared to Tiv-Model users.
- Tiv-Model users found, more often than V-Model users, that the methodology was complex and difficult to follow.
- Teaching changes that presented the Mid-level functionality of the two methodologies may have worked against Tiv-Model, as it presented too much complexity at once.
- Students still showed results that suggested Tiv-Model was perceivably inflexible.

6.3.4 Student studies - Phase 3

Phase 3 operated much like phase 2 in terms of teaching strategy, however there were several changes made from feedback in the previous phase:

- Tiv-Model had been changed visually and functionally once more
    - The model's Macro-level had been cleaned up to represent a new version, removing most of the visual noise such as arrows and small text.
- The teaching workshop had been rethought
    - It was understood from the previous workshop that time constraints pressured the students into forgoing typical methodology procedure at some points in the session. Additionally, there were misunderstandings with regards to what was required of the students during the workshop. The documentation was made simpler, and the task was reduced to core utilisation of the mid-level model to fit within the workshop time constraints.
- Class teaching was refined slightly
    - The slides were updated with the new graphics and descriptions were simplified, using analogies and examples, giving a better understanding for the students.
- Answers towards the survey were not encouraged to the same degree
    - The previous year's class setup allowed the study to be performed in an integrated manner with the class workload, this year the study was not afforded the same privilege despite being accessible through the same site. As a result, integration with the class workload was difficult, the survey was less of a focus and more of an afterthought, students felt less incentivised to pursue the study and thus results were lost.

The biggest weakness of this phase was the lack of survey replies, losing robustness of the previous phase. Instead, there were drastically different answers given for the newly reformed Tiv-Model at a lower population size, so conclusions were easy to draw but difficult to back up.

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
1	*V*	0	3	3	6	0	12	-0.25	0.866025404	0.004646537	Reject, 0.01	Tiv

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
	Tiv	0	0	0	4	2	6	-1.333	0.516397779			
2	*V*	0	0	2	8	2	12	-1	0.603022689	0.031754628	Reject, 0.05	Tiv
	Tiv	0	0	0	2	4	6	-1.667	0.516397779			
3	*V*	0	8	3	1	0	12	0.583	0.668557923	0.833826651	Accept Null	Tiv
	Tiv	1	2	3	0	0	6	0.667	0.816496581			
4	*V*	0	6	2	4	0	12	0.167	0.937436867	0.128682518	Accept Null	Tiv
	Tiv	1	3	2	0	0	6	0.833	0.752772653			
5	*V*	1	10	1	0	0	12	1	0.426401433	0.024311981	Reject, 0.05	Tiv
	Tiv	4	2	0	0	0	6	1.667	0.516397779			
6	*V*	1	6	4	1	0	12	0.583	0.792961461	0.056128983	Reject, 0.1	Tiv
	Tiv	1	5	0	0	0	6	1.167	0.40824829			
7	*V*	1	1	3	7	0	12	-0.333	0.984731928	0.741647402	Accept Null	V
	Tiv	0	2	1	3	0	6	-0.167	0.98319208			
8	*V*	0	6	4	2	0	12	0.333	0.778498944	0.739386964	Accept Null	Tiv
	Tiv	1	2	2	1	0	6	0.5	1.048808848			
9	*V*	0	1	3	7	1	12	-0.667	0.778498944	1	Accept Null	NA
	Tiv	0	1	0	5	0	6	-0.667	0.816496581			
10	*V*	2	4	1	4	1	12	0.167	1.337115847	0.003718291	Reject, 0.01	Tiv
	Tiv	0	0	0	4	2	6	-1.333	0.516397779			
11	*V*	1	5	1	5	0	12	0.167	1.114640858	0.001277044	Reject, 0.01	Tiv
	Tiv	0	0	0	4	2	6	-1.333	0.516397779			
12	*V*	0	0	3	8	1	12	-0.833	0.577350269	0.179541707	Accept Null	Tiv
	Tiv	0	0	0	5	1	6	-1.167	0.40824829			
13	*V*	1	7	3	1	0	12	0.667	0.778498944	0.217260573	Accept Null	Tiv
	Tiv	2	3	1	0	0	6	1.167	0.752772653			
14	*V*	0	5	4	3	0	12	0.166666667	0.83484711	0.003565216	Reject, 0.01	Tiv

Q	Model	SA	A	NS	D	SD	n	m	σ	p	Null Hyp?	Fav.
	Tiv	1	5	0	0	0	6	1.166666667	0.40824829			
15	*V*	2	3	2	4	1	12	0.0833	1.311372171	0.041590144	Reject, 0.05	Tiv
	Tiv	2	3	1	0	0	6	1.1667	0.752772653			
16	*V*	1	8	2	1	0	12	0.75	0.753778361	0.074640132	Reject, 0.1	Tiv
	Tiv	2	4	0	0	0	6	1.333	0.516397779			
17	*V*	0	3	2	6	1	12	-0.417	0.99620492	0.000221385	Reject, 0.01	Tiv
	Tiv	1	5	0	0	0	6	1.167	0.40824829			
18	*V*	0	4	0	8	0	12	-0.333	0.984731928	0.012255565	Reject, 0.05	Tiv
	Tiv	0	0	0	4	2	6	-1.333	0.516397779			
19	*V*	0	8	2	2	0	12	0.5	0.797724035	0.002068726	Reject, 0.01	Tiv
	Tiv	4	2	0	0	0	6	1.667	0.516397779			
20	*V*	0	4	5	3	0	12	0.083	0.792961461	0.472784444	Accept Null	Tiv
	Tiv	1	3	0	2	0	6	0.5	1.224744871			
21	*V*	0	6	5	1	0	12	0.417	0.668557923	0.006990751	Reject, 0.01	Tiv
	Tiv	2	4	0	0	0	6	1.333	0.516397779			
22	*V*	1	4	5	2	0	12	0.333	0.887625365	0.121429584	Accept Null	V
	Tiv	0	0	5	1	0	6	-0.167	0.40824829			
23	*V*	1	8	3	0	0	12	0.833	0.577350269	0.179541707	Accept Null	Tiv
	Tiv	1	5	0	0	0	6	1.167	0.40824829			

Table 6-10 - Tiv-Model comparative study phase 3 results

Question 1 - *Overall, I found the methodology difficult to use*

From question 1 there was a very drastic shift in the attitudes of Tiv-Model users, this perception trend continued throughout the remaining questions. Tiv-Model users were in unanimous disagreement with the statement, whilst V-Model users hovered around uncertainty and disagreement. Over three phases the V-Model pattern had moved towards uncertainty. The difference between phase 1 and 2 could be explained by the teaching style shift to exposing more detail, and phase 2 to 3 could be explained by the shift to lower population numbers. Tiv-Model's overhaul explained the change between phase 2 and 3, and the teaching changes that did not work in its favour between phase 1 and 2.

It could confidently be said that Tiv-Model users disagreed with the methodology being difficult to use comparatively to users of V-Model. Thus, the null hypothesis was rejected, and it could be stated that Tiv-Model, by user's perception, was easier to use.

Question 2 - *I would definitely NOT use this model to develop mechatronic systems*

There was a similar pattern in this question's results compared to question 1. V-Model and Tiv-Model's users disagreed with the statement, showing that they may use this model again. Tiv-Model users had changed the most across the 3 phases and were eager to use the methodology again.

The null hypothesis was rejected in this case, with some confidence. Tiv-Model users were against the idea of not using the model again more so than V-Model users.

Question 3 - *I would use this model instead of Pugh's TDM if I have to develop a mechatronic system*

This question received varying results across the three phases, the teaching changes made Tiv-Model stand out as the mechatronic system methodology of the two. V-Model's users' attitude towards the model's re-usability dipped during phase 2 but returned to nominal in phase 3. This could be explained by the teaching changes.

Question 4 - *I found the rules of the model clear and easy to understand*

V-Model results had a slump, as opposed to the Tiv-Model results which increased in agreeability. The lower population size explains this. Tiv-Model users results showed an indication that the changes made to the model made the rules clearer, but inferences could not be made between the models.

Question 5 - *I found that the model was suitable for this kind of project*

With the better teaching changes in place starting in phase 3, lessons were learned in phase 2, opting for simplified explanations of complex components. Thus, an attitude readjustment was visible from the students, both user groups reported an increase in agreeableness and thought that the methodology was suitable for the project.

Tiv-Model users increased greatly in agreeableness, and it could be said with some confidence that Tiv-Model was more suitable for the project from a student perspective. In this case the null hypothesis could be rejected in favour of the Tiv-Model.

Question 6 - *I found that my existing knowledge worked well with the model*

Surprisingly, V-Model user average agreeableness with this statement did not change in any meaningful way, but Tiv-Model user agreeableness increased steadily and significantly. Even though efforts were made to frame both methodologies in the context of previous knowledge. This came as a surprise as in terms of chronology, as the V-Model shared more in common with Pugh’s TDM. It could be said with a little confidence that students felt their knowledge worked better with Tiv-Model.

Question 7 - *I found that I was limited to specific means or methods in order to achieve my goal*

Through all phases, the students’ attitudes towards their freedom to design had been mixed, disagreement with the statement but hovering around uncertainty. The results had not changed significantly across the phases, despite changes to the model and to the teaching standard. More could be done to emphasise the customisability of the methodologies and the choices of methods, however the limitations could also be from the project itself. The nature of mechatronic systems demands empiricism and optimisation, and thus fewer methods were usable.

Question 8 - *I believe that the model would reduce the effort required to produce mechatronic systems*

The perception of effort required to use a methodology seemed to be reflected in how complex it seemed on the surface. When the teaching changes were introduced to phase 2, there was an increase in “perceived complexity” in Tiv-Model specifically that exposed the complexity. V-Model did not suffer in the same way as the operation of the methodology was not perceived as complex. The teaching strategy was readjusted and an increase in positive attitude towards Tiv-Model was observed. V-Model attitudes remained the same, as the Mid-level was already simple enough.

Question 9 - *Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems*

Answers had been mixed for the two methodologies. Both methodologies had similar results across the phases except for phase 2, where V-Model users disagreed with the negative connotations of the statement slightly more. The expectation of the study on the question was that V-Model would be considered more suitable, and during phase 2 that could have been the case. However, the pattern visible in this question runs counter to other questions regarding effectiveness. It seemed that teaching strategy and adjustments to simplicity did not affect the perception of effectiveness, only effort required in utilisation.

Question 10 - *I am NOT confident about applying this method in practice*

The split between the two groups in terms of confidence was evident in this question. Tiv-Model users gradually moved towards disagreement across the phases, and V-Model users maintain their confidence, but move very slightly toward agreement. The small, insignificant shift in V-Model user attitudes did not have a clear explanation, but the shift in attitude for Tiv-Model users could be attributed to methodology changes made to improve it.

It could confidently be said that Tiv-Model users were more confident in their application of the methodology than V-Model users.

Question 11 - *I found it difficult to apply the model to the project*

V-Model user attitudes made a significant jump to agreement between phase 2 and 3, and Tiv-Model in the opposite direction. It was possible that V-Model students might be projecting their feelings of the project onto the methodology when talking about difficulty. Some changes to groupings were made to the project, there were now more teams within the V-Model group that would have made administrative and communicative activities slightly more difficult than previous years. Despite this, Tiv-Model's large move to disagreement was still a significant find.

It could be said with confidence that the Tiv-Model users did not find it difficult to apply their methodology to the project when compared to V-Model users.

Question 12 - *Using this model would make it more difficult to complete mechatronic projects*

V-Model user results had remained consistent across the three phases, as expected and in line with previous observations as teaching changes did little to simplify what was already simple enough. Tiv-Model, on the other hand, with the improvements made to the model showed a very distinct movement towards disagreement for the users in this group. While this was interesting from a developmental point of view, it did little to prove anything for this experiment.

Question 13 - *This model would make it easier for designers to produce mechatronic systems*

V-Model user perception on how much easier it would be for designers to use the methodology are again consistent across the phases. Tiv-Model on the other hand dipped from the teaching changes made in phase 2 and rose again for further changes in phase 3. This movement was rather significant, but not enough to merit hypothesis rejection.

Question 14 - *Using this model would make it easier to communicate concepts in a mechatronic project*

Tiv-Model user perceptions on the communicative aspects of the methodology rose steadily across the stages, spiking at phase 3. The same pattern emerged for V-Model users, however any growth in positive perception may have been stifled with the change to the group team structure, specifically an academic instruction and outside the control of the experiment.

There was a very significant difference in the two mean attitudes, and thus it was said with confidence the Tiv-Model users felt that the model allowed easier communication.

Question 15 - *I found the model easy to learn*

Surprisingly, across the three phases, both group’s agreeableness lowered, despite changes made to make the teaching easier. Tiv-Model’s sudden positive spike in the mean was possibly attributed to the large changes in the methodology made for phase 3.

With some confidence, this evidence suggested that the new Tiv-Model was easier to learn than V-Model, comparatively and perceptively.

Question 16 - *Overall, the model's information was well presented*

The same dip in information presentation was seen from previous questions regarding the same thing in the Tiv-Model. Agreement that the information was well presented dipped a little during phase 2 and climbed drastically in phase 3. Meanwhile, V-Model's climbed and stays as high between phase 2 and 3, as not many significant changes were made to that presented information.

With a little confidence it was assumed that Tiv-Model users thought that, in the end, Tiv-Model had its information presented better than V-Model users.

Question 17 - *I would use this model again in a general product development project*

V-Model's pattern shifts towards disagreement in this question whilst Tiv-Model moves, with a spike in phase 3, to agreement. The attitude toward V-Model may be attributed to the difficulty in application experienced by the large number of teams within the V-Model group in phase 3. Tiv-Model's change was likely due to the drastic changes to the model made for phase 3.

From raw data, it could be assumed that Tiv-Model users were happier to use the model again compared to V-Model users, as the difference was incredibly significant.

Question 18 - *I found the model complex and difficult to follow*

Slowly but steadily, the agreeableness of V-Model users rose through the three phases, the most significant jump being in phase 3. Tiv-Model users were the same, however the average took a massive dip in phase 3, likely due to the changes implemented to the methodology. This was, again, likely due to the teaching protocol that showed more complexity than in phase 1.

It could be assumed with some confidence that Tiv-Model users found their methodology less complex than V-Model users.

Question 19 - *Overall, I found the model to be useful*

Usefulness of the model was not affected by teaching changes; however, the perceived effectiveness of Tiv-Model was an exception when the drastic overhaul was introduced.

It could be assumed with great confidence that phase 3 Tiv-Model users found the methodology to be more useful than V-Model users.

Question 20 - *Overall, I found that the model freely allowed me to make design decisions*

It was found that the perceived decision freedom was low on either model, with a change only being noted in stage 3. V-Model users may have been falsely attributing this lack of freedom to the model when it could possibly be the conditions of the project. The large number of teams in one group meant that decision making was hampered by the need to go through multiple channels, and concurrency was not enforced. Tiv-Model's perceived decision-making freedom was also low throughout.

Question 21 - *The Macro-level model was useful for this project*

V-Model opinions on the macro-level decreased slightly whilst Tiv-Model opinions increased greatly. The Macro-level adjustment to the Tiv-Model was the mostly likely explanation for this drastic change.

With confidence it was assumed that the Macro-level presentation of Tiv-Model was better received than the same part of V-Model.

Question 22 - *The Micro-level problem solving technique was useful for this project*

Surprisingly, Tiv-Model micro-level problem solving schema did not perform as well as expected, and differed slightly from the V-Model schema, which was uncertain. It could be assumed that it was C-QuARK's situational, limited range of uses that may have created the difference in opinion. The problem-solving schema used by V-Model XT was very generic and useful in a range of applications. Interesting data for development, but not for experimentation.

Question 23 - *The Mid-level task management was useful for this project*

The Mid-level component of both methodologies was the focus of most overhauls, so it was interesting to see here that both sets of user opinions drastically improved regarding their mid-level experience. This might be the result of the improved workshop, which focused entirely on the Mid-level use; both averages increase by roughly 0.4. This did not provide hypothesis rejection but was excellent data for development purposes.

Summary

The difference across the three phases showed the progression of both the experiment and the Tiv-Model. Phase 3 specifically showed that Tiv-Model, in its form as of the time of writing, was preferable when it came to many aspects, 13 out of the 23. Improvements that made to the model were reflected in the results, some with surprising conclusions. In general, Tiv-Model outperformed the V-Model in the areas of usefulness, presentation of information, ease of use and learning, ease of communication, confidence in implementation, utilisation of designer knowledge, suitability to the task and overall positive perception. Figure 6-10 shows the results for phase 3, 13 question showed favourable results for Tiv-Model, the rest were inconclusive.

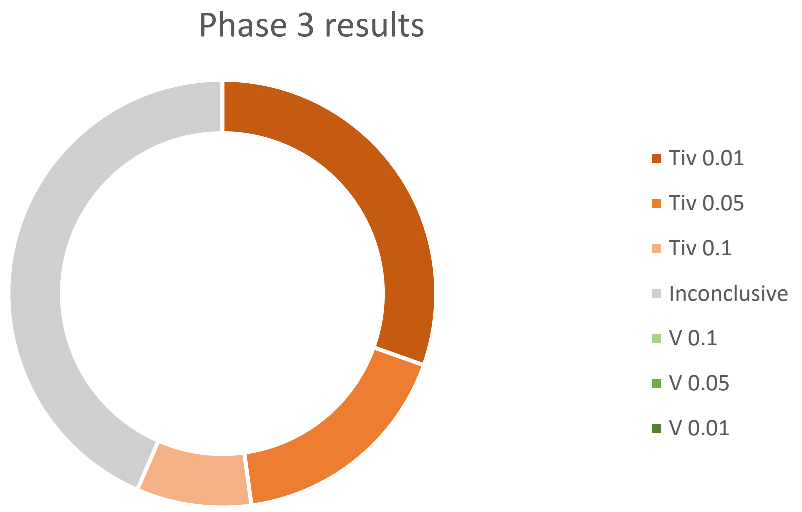


Figure 6-10 - Phase 3 hypothesis rejections

6.4 Chapter 6 summary

The validation of the Tiv-Model was performed by the Validation Square, which was also used as a guide for the verification of design methodologies. V-Square is a robust tool for the evaluation of design methods, but as was argued throughout this paper its use can logically extend to methodologies by shifting the scope of structural elements.

The V-Square has six steps for verification and validation, moving from qualitative evaluation to quantitative, covering the structure and performance of the methodology. The plan for verification and validation of the Tiv-Model was in 6 steps.

1. **Proving validity of the constructs -** Each of the principles, methods and procedure components of the Tiv-Model were determined, and citations were provided for their validity.
2. **Proving logical consistency -** It was then established that the methods work together as intended by showing a logical flow chart of information through Tiv-Model. This was compared to existing paradigms of design.
3. **Proving the suitability of example problems -** A case was made for the example problems being like the intended problems. Noting the key features of mechatronic and robotic projects, the similarities to complex systems engineering were apparent.
4. **Proving the method works for these problems -** A small case study was performed on the model used in an academic space hardware project. It was apparent that the model was indeed suitable for those kinds of projects and the features within the scope of the project were useful. The nature of the project did not allow data gathering on some of the key features, but from a high-level perspective the model was functional and viable.
5. **Proving usefulness is linked to model usage -** A series of comparative studies were performed involving a few hundred students in robotic team projects. They were split by use of a design methodology and their perceptions of those methodologies were compared. This happened over three phases of continuous improvement for Tiv-Model, as the experiment provided an opportunity to fix issues. By the end, Tiv-Model was considered just as viable in most aspects as V-Model, an industry standard, and excelled in a small majority of other aspects, according to the students.

Through provision of these key components of the V-Square, based on the evidence provided throughout the thesis It could be established that Tiv-Model satisfied these criteria. Validity of the components of the methodology were verified by literature and a case was made for their logic. An argument was provided for the example problems being representative of the intended problems and it was shown that the methodology works under the example conditions. Data was then provided showing that Tiv-Model was attributed to the performance through benchmarking. With this, solid evidence is provided for the first 5 steps of the V-Square. As per V-Square evaluation, enough information was given to make the “leap of faith” to step 6.

Table 6-11 below shows the combined results of the final phase of experiments, showing that 13 of the 24 questions demonstrate the students favouring Tiv-Model more than V-Model. While this was not reflective of the results in the phase 1, an iterative and continuous improvement methodology led to an improved Tiv-Model and overall testing procedure.

Survey question	Favoured Model, p-value
Overall, I found the methodology difficult to use	Tiv-Model, 0.01
I would definitely NOT use this model to develop mechatronic systems	Tiv-Model, 0.05
I would use this model instead of Pugh's TDM if I have to develop a mechatronic system	Neither
I found the rules of the model clear and easy to understand	Neither
I found that the model was suitable for this kind of project	Tiv-Model, 0.05
I found that my existing knowledge worked well with the model	Tiv-Model, 0.1
I found that I was limited to specific means or methods in order to achieve my goal	Neither
I believe that the model would reduce the effort required to produce mechatronic systems	Neither
Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems	Neither
I am NOT confident about applying this method in practice	Tiv-Model, 0.01
I found it difficult to apply the model to the project	Tiv-Model, 0.01
Using this model would make it more difficult to complete mechatronic projects	Neither
This model would make it easier for designers to produce mechatronic systems	Neither
Using this model would make it easier to communicate concepts in a mechatronic project	Tiv-Model, 0.01
I found the model easy to learn	Tiv-Model, 0.05
Overall, the model's information was well presented	Tiv-Model, 0.1
I would use this model again in a general product development project	Tiv-Model, 0.01
I found the model complex and difficult to follow	Tiv-Model, 0.05
Overall, I found the model to be useful	Tiv-Model, 0.01
Overall, I found that the model freely allowed me to make design decisions	Neither
The Macro-level model was useful for this project	Tiv-Model, 0.01
The Micro-level problem solving technique was useful for this project	Neither
The Mid-level task management was useful for this project	Neither

Table 6-11 - Combined experiment results

Normally, this would be sufficient to claim validity of the Tiv-Model, but to ensure that the evaluation was performed with as little uncertainty as possible, one final series of studies was performed with the Tiv-Model. A focus group, with industry veterans participating, was organised to levy critique and feedback on the state of the Tiv-Model. This would be the closest means of exposing the model to the industry environment.

Summary at a glance

- ♦ Validation Square is introduced, with 6 steps that take Tiv-Model through V&V;
    1) Accepting construct validity – The elements that make up the Tiv-Model are valid
    2) Accepting method consistency – The elements are compatible and relevant
    3) Accepting example problems – The test setup is valid
    4) Accepting relevance in examples – Tiv-Model looks useful in the test problem
    5) Accepting usefulness in examples – Tiv-Model was the reason for usefulness
    6) Accepting usefulness outside examples – Tiv-Model considered useful by users
- ♦ The first 5 steps are covered in this chapter via a case study and a series of iterative comparative studies
- ♦ The comparative studies showed that Tiv-Model was not seen as useful as the benchmark, V-Model
- ♦ Improvements were made to the Tiv-Model, in the final evaluation Tiv-Model outperformed V-Model in at least 13 of the 23 categories

Next…

- ♦ The Tiv-Model undergoes exposure to a focus group study of industry veterans
- ♦ This invites critique and final changes to the Tiv-Model and finishes V-Square step 6

Chapter 7

Focus group study

To assist in the validation of the model, a focus group was hosted with 6 industry experts from various engineering disciplines and backgrounds. The goal was to present the Tiv-Model to the group and capture their thoughts on it. The results showed that Tiv-Model, while addressing the key principles of system design, does not do well at capturing this information in the macro-level model.

In this chapter:

- **Final verification step of thesis**
- **Focus group overview**
- **Focus group results**
- Actions performed on Tiv-Model due to results

7.1 Focus group interview

To assist the validation of the Tiv-Model, some exposure to the context of the intended problem space was desired (although not required by the V-Square method). It would have been both difficult and costly to use the Tiv-Model in an industry setting for an actual project. Instead, a focus group was conducted with several industry veterans with the goal of critiquing the Tiv-Model from an industry perspective.

In short, the primary finding of the focus group was that there were many aspects of the Tiv-Model that were not visibly captured in the high-level model. The participants rightly pointed out that many of the elements of a design methodology that they were concerned with did not appear on the macro-level Tiv-Model diagram. It was explained that these show up in the training resources for the model, however the lack of depth of the macro-model, coupled with the very short introductory presentation left the participants wondering about some of the details that would aid them in deciding what they should do with the model.

Another key conclusion was regarding the applicability of Tiv-Model, there was some concern over what kinds of situations the model was useful for, and whether they would be useful for specific examples. There were comments on how some stages of the model may not be applicable in a specific scenario, and in some cases the description would be too open to interpretation to maintain adherence.

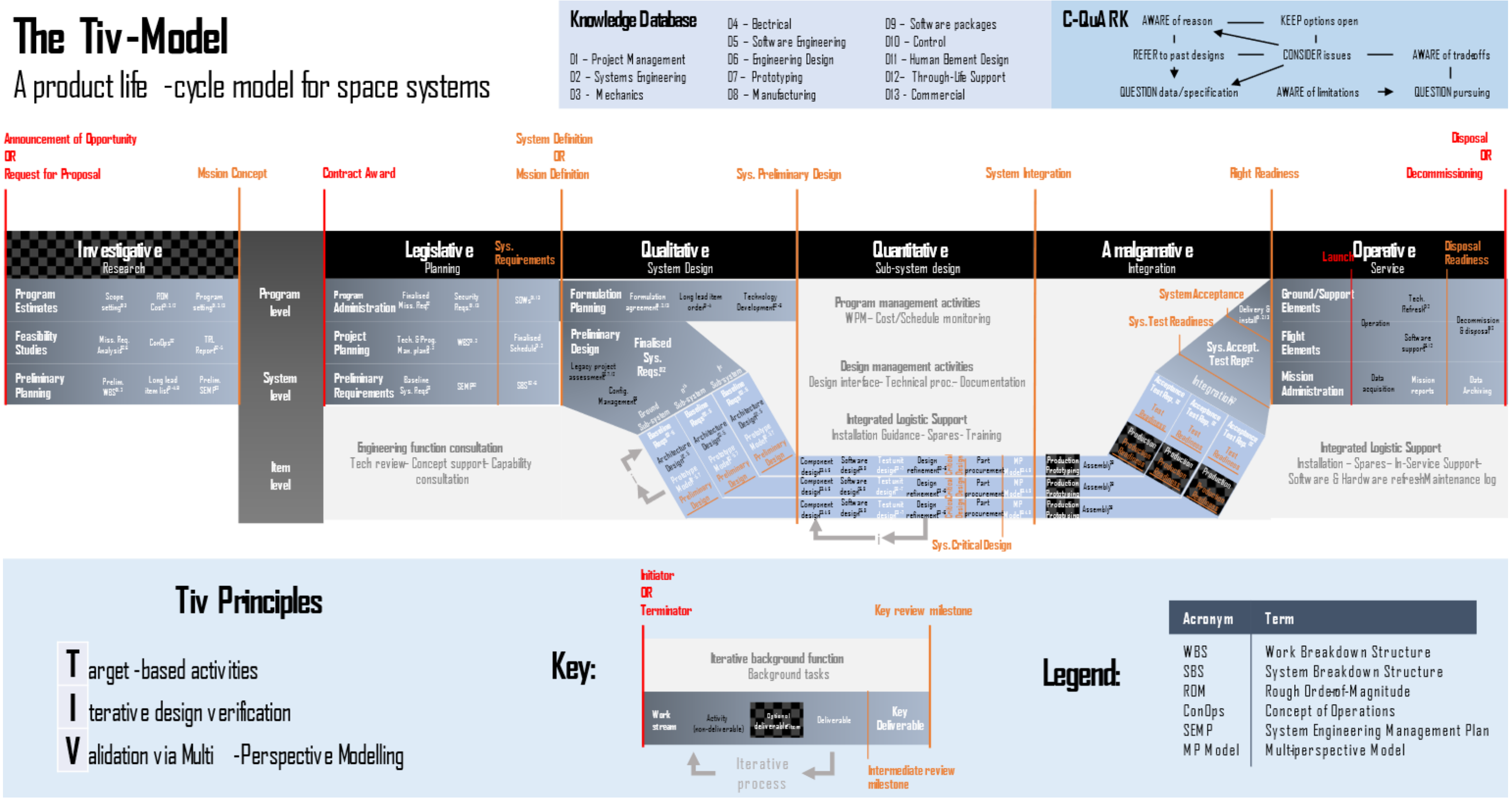
Other conclusions from the group were minor, regarding observations and questions of the purpose of certain aspects of the model and how this model might be used.

After the focus group had adjourned, a survey was sent out to gather final thoughts from the participants and what they felt some of the key issues were, and how to address them. This further reinforced the two main points from above.

With all the participants thoughts gathered, the questions and comments from the focus group were gathered (shown in Appendix **Error! Reference source not found.**), translated into issues and eventually general actionable items to perform on the Tiv-Model. These actions were designed to adjust the model in line with industry expectations, these are shown in Table 7-3.

The outcome of the focus group is that the Tiv-Model underwent some significant change to reflect some of the expectations that industry members had of it. These were mainly visual and informational aspects used to communicate the model more effectively, however some were considerations that were not present in the design phase of the Tiv-Model.

The final iteration of the Tiv-Model has a visual overhaul of the macro-level of Tiv-Model to communicate the aspects that were of concern to the focus group. The Knowledge Database was upgraded to a macro-level concept as it is organisational, and the terminology behind some of the deliverables and sub-tasks were changed. The final version of Tiv-Model is shown in Figure 7-1.



Acronym	Term
WBS	Work Breakdown Structure
SBS	System Breakdown Structure
ROM	Rough Order-of-Magnitude
ConOps	Concept of Operations
SEMP	System Engineering Management Plan
MP Model	Multiperspective Model

Figure 7-1 - Final version of Tiv-Model

7.2 Focus group setup

The Tiv-Model focus group was organised by first contacting potential participants. This included a shortlist of people who are contacts with the University, as well as some other networked contacts. Of the 12 people contacted, 7 agreed to participate in the focus group and filled out their consent forms.

Next, the timing of the focus group session was organised by putting out an availability poll of all dates over a two-week period, with a range of 2hr slots given each day. The participants filled out the form to find which common dates and times they were free.

The focus group took place over Zoom, due to the participant location limitations and COVID-related guidelines in place at the time. Participants were also given introductory material to read on the Tiv-Model, to prime them for the focus group. This was not in-depth training material, but rather overview documentation to use as a reference. The materials given to participants can be reviewed in Appendix B.ii and **Error! Reference source not found.**.

The intent of the focus group was to establish the group's opinion on the perceived usefulness of several aspects of Tiv-Model:

Macro-level concepts	Micro-level concepts
Deliverable/goal-based tasks	C-QuARK
Multi-perspective modelling	
Model timeline	
Critical tasks	
Review schedule	
Mid-level concepts	**Other aspects**
Knowledge database	Novelty
Sub-task management	Key benefits/drawbacks
Deliverables	Impact on cost/quality/time
Reviews	Organisation implementation
	Suitability

The opinion of the participants regarding the above aspects would be asked as key questions during the focus group session. However, the main objective was to get the initial perception and reaction to the Tiv-model, and to allow the participants to organically bring up important points.

The focus group was designed around a typical focus group strategy; firstly, an introductory overview of the item the group would be discussing, then a length of time where questions were asked by participants, with discussion being prompted by the host via question prompts. The 2hr long session schedule was formed, shown in Table 7-1.

Session Item	Length of time	Cumulated time
Congregation and introductions	5	5m
Overview of focus group	5	10m
Presentation on Tiv-Model	35	45m
Open floor to questions	15	60m
Opening questions	25	1h 25m
Key questions	30	1h 55m
Session wrap-up	5	2hr

Table 7-1 - Focus group rough schedule

7.3 Focus group findings

The focus group session successfully took place over the course of the two hours, with the first 40 minutes spent giving the participants contextualising information, and the remainder of the session being primarily guided by the participants in gaining understanding in the Tiv-Model.

The initial plan involved the participants being asked a series of prompting questions to achieve feedback. However, the participants had many questions regarding the Tiv-Model and took opportunities to provide most of their feedback by commenting on the answers to those questions. This left very little time at the end to follow the planned flow of the focus group, and thus the opening questions were dropped, moving straight to some key questions before wrapping up the session.

The full list of comments and questions made by the participants over the course of the focus group is shown in Table 7-2.

Note: "Item" indicates the item number of the question or comment, "P No." indicates the number of the participant who originated the comment/question.

Item	Question/Comment	P No.
1	With regards to its macro-level modularity, what are the mandatory aspects/stages of Tiv-Model?	7
2	Who is this model for? For a company? Is it driven by industry needs or academic research?	6
3	What is the aim of this model? What is it really?	6
4	The model is missing information that tells the user what is happening within the design stages, information presented like C-QuARK is simple enough to demonstrate this.	6
5	The wording seems flawed and vague on the macro-model, it does not divulge the contents of the stage.	6
6	It would be nice if you could take us through the model, or show us a simple example.	6
7	The risk management side of the design is missing.	6
8	A project we're working on uses the term "responsible innovation" instead of legislation.	6
9	Given that V-Model subdivides the process from system to unit, how does Tiv-Model show this subdivision?	3
10	How does the verification and validation stage of the Tiv-Model address sub-system and system verification?	3
11	The process should follow ECSS standards for electrical production and test acceptance.	3
12	The beauty of the V-Model is that each stage corresponds with its testing methods.	7
13	The Tiv-Model feels a bit linear, how can you get feedback from testing to requirements?	7
14	Does this model target systems engineers or project management?	3
15	Is this being sold to the organisation or the systems engineer?	3
16	I don't see the connection between the macro and micro level.	2

17	Is it possible to use the methodology without using C-QuARK?	2
18	I think having multiple levels in the model can hinder the “sell” of the model.	2
19	Which specific aspect of the space industry does the Tiv-Model improve and how does it tackle it?	4
20	Why is the evaluative stage positioned in the Tiv-Model where it is? You can do more modelling and testing before that point.	5
21	Keep in mind that tools that are more generally proficient at design, may not be especially good in a particular aspect.	4
22	What are the necessary conditions for Tiv-Model to work on a project?	4
23	What is the scope of the operative step? There is a lot of ground system elements to consider.	3
24	The scope of the operative phase seems too general and vague to get meaning from it.	3
25	The model seems difficult to apply to a real work scenario.	7
26	The model should either be displayed as fully encapsulating and generic, or broken down into separate versions for separate scenarios and stages.	7
27	Every stage of this is too open to interpretation.	7
28	The people barrier is a massive aspect of adoption.	7
29	Why are end-to-end tasks (like the PM aspect) not upfront or as highlighted?	4
30	Careful of implementing the methodology where it doesn’t belong. Adopting agile within Participant 4’s company mechanical team did not have the intended results, partly due to the nature of the methodology, partly due to misunderstanding of the model.	4
31	Is there a link between Tiv-Model and model-based system engineering?	3
32	The Tiv-Model is interesting because it captures the phases outside of the design work stream, especially at the start i.e. Investigative and Legislative.	2
33	Tiv-Model captures well the encompassing issues of the project-wide scope. What it does not capture well is the detail within those phases.	3
34	Tiv-Model appears to be quite quality focused.	7
35	Tiv-Model might cause time and cost to suffer, partly due to implementation barriers.	7
36	Consider tracking costs, i.e., assigning costs to a key deliverable.	5
37	There are opportunities within Tiv-Model to help plan cost.	5
38	In space industry, time is cost.	3
39	Sharing information on the Tiv-Model in the company, as part of and after adoption, can make the difference.	3
40	Ultimately, the greatest end result of the methodology will be seen by the client (should the methodology work well).	4
41	Project manager seems to benefit the most from the Tiv-Model.	1,3
42	Project design authorities will also benefit.	7
43	Tiv could be a good tool for a customer who designs like ESA.	3
44	You need to have the client’s support to make this model successful.	4
45	What is the innovative twist that the Tiv-Model brings to the engineering process?	7
46	Tiv-Might do better with space start-ups, as large systems integrators add complexity.	7

Table 7-2 - Tiv-Model focus group questions and comments

These were then broken down into groups based on the kind of observations that were made. In all, 4 types of observations could be classified, along with a group of minor observations, shown in Table 7-3.

Question/Comment	Observation
4, 5, 6, 9, 10, 12, 16, 17, 20, 23, 24, 26, 27, 29, 33	*The Tiv-Model does not display the required information on the Macro-model*
1, 3, 18, 19, 21, 22, 25, 30, 45, 46	*The applicability of the Tiv-Model is not clear*
2, 14, 15, 39, 44	*The responsible parties and users are not clear*
7, 11,13, 31	*Tiv-Model is missing some critical aspect*
8, 28, 32, 34, 35, 36, 37, 38, 40, 41, 42, 43	*Minor notes/comments*

Table 7-3 - Tiv-Model focus observation matrix

From this table of classified observations, an action plan was put in place to amend the Tiv-Model based on participant feedback. Each of the observation categories was analysed, and actions were performed to address these observations. The following sub-sections summarise the general conclusions relating to the relevant observation.

7.3.1 Observation 1 – Information displayed within Tiv-Model

The most common comment or question placed during the focus group session revolved around the amount of information that was on display in the Tiv-Model's macro-level. In general, the participants felt that there was a lack of critical information on display at the highest level, leading them to ask how the Tiv-Model deals with certain aspects of the design lifecycle.

The primary conclusion from this category of items was that, while the intention of the Tiv-Model was to address these features of the system design lifecycle, it could be argued that the macro-level model did not capture these aspects.

The action made in addressing the comments in this observation was to make suitable changes to the macro-level model.

Item	Question/Comment	Reqs
4	The model is missing information that tells the user what is happening within the design stages, information presented like C-QuARK is simple enough to demonstrate this.	Comprehensibility
5	The wording seems flawed and vague on the macro-model, it does not divulge the contents of the stage.	Comprehensibility
6	It would be nice if you could take us through the model, or show us a simple example.	Learnability
9	Given that V-Model subdivides the process from system to unit, how does Tiv-Model show this subdivision?	Structuring
10	How does the verification and validation stage of the Tiv-Model address sub-system and system verification?	Structuring
12	The beauty of the V-Model is that each stage corresponds with its testing methods.	Comprehensibility
16	I don't see the connection between the macro and micro level.	Problem Solving Cycle
17	Is it possible to use the methodology without using C-QuARK?	Problem Solving Cycle
20	Why is the evaluative stage positioned in the Tiv-Model where it is? You can do more modelling and testing before that point.	Structuring
23	What is the scope of the operative step? There is a lot of ground system elements to consider.	Flexibility
24	The scope of the operative phase seems too general and vague to get meaning from it.	Flexibility
26	The model should either be displayed as fully encapsulating and generic, or broken down into separate versions for separate scenarios and stages.	Applicability
27	Every stage of this is too open to interpretation.	Flexibility
29	Why are end-to-end tasks (like the PM aspect) not upfront or as highlighted?	Structuring
33	Tiv-Model captures well the encompassing issues of the project-wide scope. What it does not capture well is the detail within those phases.	Structuring

Table 7-4 - Focus group observation list 1

Comprehensibility – Item 4, 5, 12

Some participants were concerned about how the model portrayed information. Items 4 and 5 were observations that highlighted the lack of information visible with regards to the work that should take place within a stage. While the macro-level model should remain minimalist with regards to information, there should be an amount present to remind someone educated in the Tiv-Model of what work should take place and when.

To meet the expectations of industry, the Tiv-Model macro-level view had the Stage names altered to alleviate vagueness by adding a subtitle, and the activities within stages were reworked to show more of the work that happens within that design stage.

Item 12 concerned the V-Model’s ability to show the requirements each system level was verified against by linking it back to the other side of the V.

It was decided that some representation of the lower system levels was required to be shown on the macro-level model, and the “V” element is a useful tool to display this information. Thus, the Tiv-Model’s macro-level timeline was altered to show the lifecycle of the component and sub-system design work.

Structuring – Item 9, 10, 20, 29, 33

Item 9 and 10 refer to the V-Model’s superior ability to show the sub-system and component levels on the macro-level model by using the depth of the “V”.

As above, a change is made to the Tiv-Model to utilise a method of displaying information such as this.

Item 20 is a question that probes the logic of containing the “Evaluative” step at the end of the design workflow. The reasoning behind this was that this is where system verification occurs, however the participants rightfully point out that iterative evaluation occurs throughout the design process and at each of the system levels.

Again, as above, an overhaul was made to the Tiv-Model stages to clarify the difference between iterative evaluation and acceptance testing.

Item 29 highlights the lack of an emphasis of end-to-end tasks, and other Project Management aspects. Tiv-Model assumed that end-to-end resource allocation would not be displayed in the model as these were assumed as part of the process given that the PM is involved in the management of all of the stages shown in the Tiv-Model.

Item 33 points out that detail is lacking in the macro-model. The intention of the macro-level model was to keep the detailed information out of view, having that relayed to the user via an educational look at the Tiv-Model. The macro-level model would then only be used as a refresher.

However, there is merit in containing more useful information in the high-level view of the Tiv-Model, so changes were made to the macro-level model to contain more contextual information to help detail what happens in the Tasks.

Problem Solving Cycle – Item 16, 17

Items 16 and 17 were both comments regarding the micro-level problem solving, checking to make sure that the micro-level is an important and mandatory part of the Tiv-Model. The C-QuARK method has always been an important but optional tool included within the Tiv-Model to aid the novice engineer in performing some problem-solving action in the design context.

Flexibility – Item 23, 24

Items 23 and 24 were observations about the scope of stages within the Tiv-Model macro-level, indicating that perhaps the moderate vagueness of the wording in the stage does not capture the full scope of each stage, particularly the Operative stage.

Applicability – Item 26

The comment made as part of item 26 called for the model to be more specific about its application. Ideally, the model should either be general use and vague, or be for a specific use (or series of specific uses) and have independent model variants that should be used in those scenarios.

Learnability – Item 6

Based on many of the comments and questions made over the course of the focus group, it became quite clear that the content that was being shown to the industry veterans was not precisely what they needed to know, as many of the questions were about the intricate functions of the model and not the theory behind those decisions. This was exemplified no better than in Item 6, where a participant indicates that they are not sure how the model would operate.

7.3.2 Observation 2 – Applicability of Tiv-Model

There were a significant number of comments and questions about the applicability of Tiv-Model, especially with regards to the kinds of projects that would find the Tiv-Model useful. Other questions were directed at the overall aim of the Tiv-Model, and what is considered “mandatory” practice while using it. This was likely due to, again, missing, or unclear information from the material.

With this observation, the devised action was to clearly define these aspects more clearly in the literature and present on the model.

Item	Question/Comment	Reqs
1	With regards to its macro-level modularity, what are the mandatory aspects/stages of Tiv-Model?	Flexibility
3	What is the aim of this model? What is it really?	Validity
18	I think having multiple levels in the model can hinder the “sell” of the model.	Comprehensibility
19	Which specific aspect of the space industry does the Tiv-Model improve and how does it tackle it?	Problem Specificity
21	Keep in mind that tools that are more generally proficient at design, may not be especially good in a particular aspect.	Problem Specificity
22	What are the necessary conditions for Tiv-Model to work on a project?	Problem Specificity
25	The model seems difficult to apply to a real work scenario.	Applicability
30	Careful of implementing the methodology where it doesn’t belong. Adopting agile within Participant 4’s company mechanical team did not have the intended results, partly due to the nature of the methodology, partly due to misunderstanding of the model.	Problem Specificity
45	What is the innovative twist that the Tiv-Model brings to the engineering process?	Innovativeness
46	Tiv-Might do better with space start-ups, as large systems integrators add complexity.	Problem Specificity

Table 7-5 - Focus group observation list 2

7.3.3 Observation 3 – Responsible parties of Tiv-Model

There appeared to be some confusion from the participants about who the responsible parties are when utilising or implementing Tiv-Model. It became clear from the comments that the participants were making that this information was not well communicated in the presentation materials.

To address these comments, various minor actions were taken to improve communication of the responsible parties.

Item	Question/Comment	Reqs
2	Who is this model for? For a company? Is it driven by industry needs or academic research?	Applicability
14	Does this model target systems engineers or project management?	Structuring
15	Is this being sold to the organisation or the systems engineer?	Comprehensibility
39	Sharing information on the Tiv-Model in the company, as part of and after adoption, can make the	Learnability

	difference.	
44	You need to have the client's support to make this model successful.	Applicability

Table 7-6 - Focus group observation list 3

7.3.4 Observation 4 – Missing considerations of Tiv-Model

Over the course of the focus group, the participants made comments about some aspects of systems engineering and design that were not considered as part of the design of Tiv-Model.

To address this, the participant comments and questions were taken on board, and the concept they were referring to was further researched to deduce its applicability to the Tiv-Model. If the content was applicable, it would be implemented into the Tiv-Model.

Item	Question/Comment	Reqs
7	The risk management side of the design is missing.	Reliability
11	The process should follow ECSS standards for electrical production and test acceptance.	Compatibility
13	The Tiv-Model feels a bit linear, how can you get feedback from testing to requirements?	Verification
31	Is there a link between Tiv-Model and model-based system engineering?	Verification

7.3.5 Observation 5 – Other observations of Tiv-Model

In addition to the 4 categorisations of the questions and comments above, some miscellaneous and positive comments about the Tiv-Model were also recorded. These comments and questions did not require any actions in particular but were worth noting to help verify certain aspects of the Tiv-Model that performed positively with the focus group or other things that should be considered.

No actions were required for these items, but they were analysed to show their importance.

Item	Question/Comment	Reqs
8	A project we're working on uses the term "responsible innovation" instead of legislation.	Innovativeness
28	The people barrier is a massive aspect of adoption.	Applicability
32	The Tiv-Model is interesting because it captures the phases outside of the design work stream, especially at the start i.e. Investigative and Legislative.	Structuring
34	Tiv-Model appears to be quite quality focused.	Effectivity
35	Tiv-Model might cause time and cost to suffer, partly due to implementation barriers.	Efficiency
36	Consider tracking costs, i.e., assigning costs to a key deliverable.	Efficiency
37	There are opportunities within Tiv-Model to help plan cost.	Efficiency
38	In space industry, time is cost.	Efficiency
40	Ultimately, the greatest end result of the methodology will be seen by the client (should the methodology work well).	Competitiveness
41	Project manager seems to benefit the most from the Tiv-Model.	Structuring
42	Project design authorities will also benefit.	Structuring
43	Tiv could be a good tool for a customer who designs like ESA.	Compatibility

Table 7-7 - Focus group observation list 5

7.4 Focus group actions

After categorising the information gained from the focus group, actions were determined to address the items that required some adjustment. The list of actioned items is shown in Table 7-8.

Item	Action group	Action
1	Applicability of Tiv-Model	Change the Tiv-Model to show acceptable modularity
2	Responsible parties of Tiv-Model	Ensure future teaching materials addresses issues
3	Applicability of Tiv-Model	Ensure future teaching materials addresses issues
4	Information displayed within Tiv-Model	Change the Tiv-Model to include task-level work details
5	Information displayed within Tiv-Model	Change the Tiv-Model to include task-level work details
6	Information displayed within Tiv-Model	Ensure future teaching materials addresses issues
7	Missing considerations of Tiv-Model	Research into new concepts before deciding on application
8	Other observations of Tiv-Model	Research into concept before deciding on application
9	Information displayed within Tiv-Model	Change Tiv-Model to show sub-system/component level and relevant verification metric
10	Information displayed within Tiv-Model	Change Tiv-Model to show sub-system/component level and relevant verification metric
11	Missing considerations of Tiv-Model	Research into new concepts before deciding on application
12	Information displayed within Tiv-Model	Change Tiv-Model to show sub-system/component level and relevant verification metric
13	Missing considerations of Tiv-Model	Change Tiv-Model to show sub-system/component level and relevant verification metric
14	Responsible parties of Tiv-Model	Ensure future teaching materials addresses issues
15	Responsible parties of Tiv-Model	Ensure future teaching materials addresses issues
16	Information displayed within Tiv-Model	Tie Tiv-Model levels together by linking in one diagram
17	Information displayed within Tiv-Model	Tie Tiv-Model levels together by linking in one diagram
18	Applicability of Tiv-Model	Tie Tiv-Model levels together by linking in one diagram
19	Applicability of Tiv-Model	Ensure future teaching materials addresses issues
20	Information displayed within Tiv-Model	Change model to show iterative evaluation, with acceptance milestones
21	Applicability of Tiv-Model	Change the Tiv-Model to show acceptable modularity
22	Applicability of Tiv-Model	Re-evaluate and re-state the working conditions of Tiv-Model
23	Information displayed within Tiv-Model	Change the Tiv-Model to include task-level work details
24	Information displayed within Tiv-Model	Change the Tiv-Model to include task-level work details
25	Applicability of Tiv-Model	Re-evaluate and re-state the working conditions of Tiv-Model
26	Information displayed within Tiv-Model	Change the Tiv-Model to show acceptable modularity
27	Information displayed within Tiv-Model	Change the Tiv-Model to include task-level work details

Item	Action group	Action
28	Other observations of Tiv-Model	No action
29	Information displayed within Tiv-Model	No action
30	Applicability of Tiv-Model	Re-evaluate and re-state the working conditions of Tiv-Model
31	Missing considerations of Tiv-Model	Research into new concepts before deciding on application
32	Other observations of Tiv-Model	No action
33	Information displayed within Tiv-Model	No action
34	Other observations of Tiv-Model	No action
35	Other observations of Tiv-Model	No action
36	Other observations of Tiv-Model	Research into new concepts before deciding on application
37	Other observations of Tiv-Model	Research into new concepts before deciding on application
38	Other observations of Tiv-Model	No action
39	Responsible parties of Tiv-Model	No action
40	Other observations of Tiv-Model	No action
41	Other observations of Tiv-Model	No action
42	Other observations of Tiv-Model	No action
43	Other observations of Tiv-Model	No action
44	Responsible parties of Tiv-Model	No action
45	Applicability of Tiv-Model	Ensure future teaching materials addresses issues
46	Applicability of Tiv-Model	Re-evaluate and re-state the optimal working conditions of Tiv-Model

Table 7-8 - Full action list post-focus group

7.4.1 Action 1 – Change the Tiv-Model to show task-level work details

Many of the concerns with the Tiv-Model were centred around a lack of critical detail on the macro-level model. Most of these comments were referring specifically to the stage and task level details. To display the necessary information, fidelity of the stage and task workflow would be required.

Tiv-Model’s workflow now shows more key deliverables and indicates the rough order in the timeline of activities. External and internal deliverables are now just deliverables, as the distinction between External and Internal was not meaningful. Now key deliverables are clearly portrayed across the points in time they are expected in the lifecycle and leading up to the review milestones. An example of the expanded deliverables can be seen in Figure 7-5.

7.4.2 Action 2 – Change the Tiv-Model to show sub-system/component level breakdown and their relevant verification metric

The focus group participants agreed that V-Model had an advantage when it came to simplifying the concept of requirements-based verification. On the model itself, the acceptance test on the right side of the "V" directly coincides horizontally with the acceptance criteria. Tiv-Model required something like this concept to demonstrate how sub-system and components are verified relative to the project lifecycle and to incorporate its multi-perspective evaluation method.

This was achieved by altering the axes of the Tiv-Model, which now shows on its side, left to right. The X-axis is time over the project length, and the Y-axis now indicates the rough level that the workstream is at. For example, development stages of the Tiv-Model work at the component and sub-system level, while the concept design and contract drafting stages generally operate at the system and program level of work. This distinction is shown in Figure 7-2.

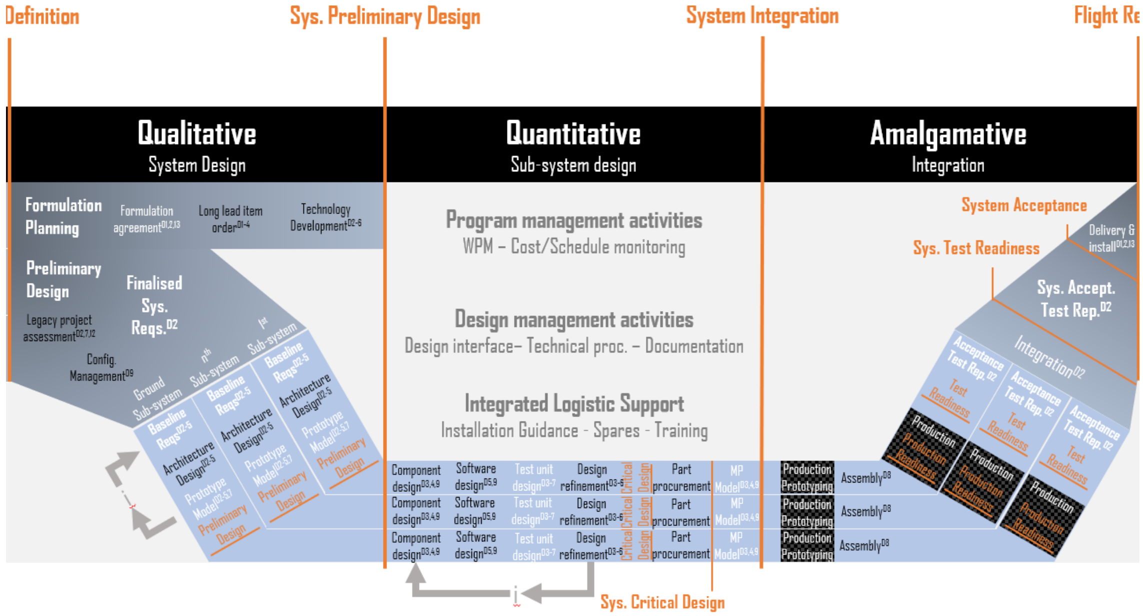


Figure 7-2 - Y-axis showing system level breakdown and X-axis showing progression of work

7.4.3 Action 3 – Change the Tiv-Model to show acceptable modularity

Many questions from the participants indicated the limitations of Tiv-Model's modularity was not clear. To clarify this, steps were taken to indicate on the macro-level model which components were modular, and which were not.

This was accomplished by Indicating on the model, via colour coding, which elements are modular. For example, the PRR is a sub-system level review that is used for items that go into production, i.e., more than one unit. This is not a useful review to have on one-off items, and thus retains a grey and black background to show its modularity from the model. Another example is the Investigative stage, which is not needed in a project where legacy items are used, or a bidder has already been selected, as some of the work falls into the preceding stage. This is shown in Figure 7-3.

Figure 7-3 - Three examples of modular aspects, with black hatched backgrounds

7.4.4 Action 4 – Tie Tiv-Model levels together by linking in one diagram

The existence of macro, mid and micro levels was a source of confusion for the industry veterans, who clearly stated that this lack of simplicity could pose a threat to the adoption of the Tiv-Model. If not, it would likely cause learnability to suffer. Tying the perspectives together in one combinatorial view may make this easier, providing one image that will encapsulate everything Tiv-Model has to offer.

Thus, the macro-level Tiv-Model was altered to include reference to the remaining components of the Tiv-Model; C-QuARK and the Knowledge Database. C-Quark was adopted as part of the Tiv-principles, now displayed on the macro-level model. This feature is now displayed as it appears in Figure 7-4.

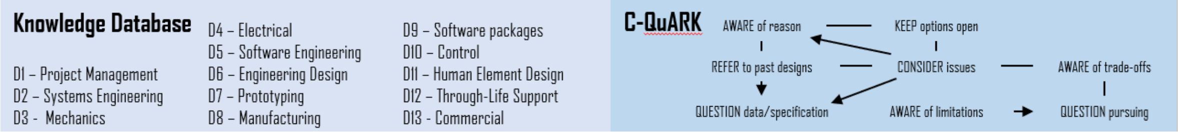


Figure 7-4 - The Knowledge Database and C-QuARK as they appear in Tiv-Model

The knowledge database has been adopted within the macro-model, with each of the deliverables showing at least one relevant knowledge realm in superscript next to the item. The macro-level model also shows the baseline for the knowledge database, i.e., the essential expertise elements in complex systems engineering. The Knowledge database, as it now appears in the Tiv-Model as a reference is shown in Figure 7-5.

Figure 7-5 - Deliverables showing the Domains relevant to the work

7.4.5 Action 5 – Re-evaluate and re-state the optimal working conditions of Tiv-Model

Several comments were made on what the suitable, required, and ideal operating conditions of the Tiv-Model were. Although this was not made clear in the presentation material to begin with, this may also be since Tiv-Model was designed with various types of project in mind. However, the apparent linearity of the Tiv-Model in its state at the time of the presentation left the participants certain that this would be more mechanically or mechatronically inclined. However, Tiv-Model exists to be suitable for systems integration, thus some of the complexity of the previous iterations of the model were brought back to satisfy this type of project.

The model's core use case was shifted to large scale systems. This meant that the structure of the model would have to fully embrace and commit to the long-term project requirements of multi-sub-system products and move away from the smaller and simpler mechatronic projects. This was manifested as a move away from the total modularity of the Tiv-Model variants seen previously and instead means embracing systems engineering fully, including overhead elements such as configuration management and layers of stage-by-stage testing. In general, this also means a parting from linear elements of design, and instead iterative evaluation of design choices before key project stages. This ensures that issues can be cleared before production.

7.4.6 Action 6 – Ensure future teaching materials addresses issues

The nature of the questions from the participants spurred an insightful look into the content being communicated to the focus group. After some reflection, it was found that more could have been done to communicate the key information that was needed in the focus group. Alternatively, this information could have been better contained within the displayable components of the model, thus actions were taken to include this information for future learning sessions.

Some information that was suggested by the participants has now been shown on the diagram, such as how the knowledge database connects to tasks, how modularity works within the model, the rough timeline of deliverables within the stage, and how the work is classified based on system or sub-system level. These changes are mostly discussed above, and the sub-system and system-level changes are focused on below.

7.4.7 Action 7 – Change the Tiv-Model to show iterative evaluation with acceptance milestones

To reflect the iterative nature of evaluation, the focus group participants expected there to be a distinct reference to this in the appearance of the Tiv-Model macro-level. This was not the case, as this evaluation process was only contained in the deeper details of the Tiv-Model teaching material. Thus, actions were taken to implement this into the macro-level view.

The macro-level now reflects the nature of verification of design against requirements, much like the V-Model. In the development track, the work is seen to drop on the Y-axis to indicate a shrinking in work scope and increase in detail at the sub-system and component level. When checking the work on the right-hand side of the V, this allows the user to check what the activity is validated against. An example of this is shown in Figure 7-6.

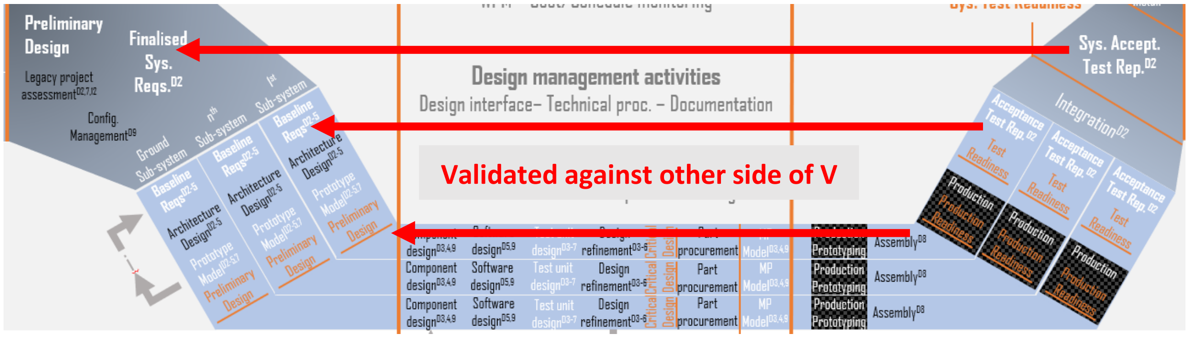


Figure 7-6 – Cross-referencing requirements when validating

7.4.8 Action 8 – Research into new concepts before deciding on application

Many of the topics discussed in the focus group session related to new or novel engineering design concepts that could play a part in the novel aspect of Tiv-Model. These responses were collected for later review as potential additions to the Tiv-Model's arsenal of research-based principles. After some consideration, a handful of the options were implemented for use within the Tiv-Model, with their consideration reflected within the requirements.

Risk management

The first concept mentioned was risk management. At a business level, risk management refers to the financial element of project, at the project level it refers to risk to progress, and at a technical level risk management is often about safety. The vagueness of this participant's statement does not exclude any of these interpretations for inclusion in the Tiv-Model. For technical and business-related risk, it was considered outside of the scope to add to the Tiv-Model. Project level risk was implemented into the newer Tiv-Model, these risks would be part of an analysis done in the Technical and Project Management Plans deliverable within the Legislative stage. Additionally, risk assessment and mitigation can take place from within the Systems Engineering Management Plan in the same stage. Risk management outside of that scope is not captured in the Tiv-Model.

Space systems engineering standards

The second concept was to include the European Cooperation for Space Standardisation (ECSS) standards for testing, but more generally this can be taken to mean inclusion of ECSS and other standards in general. On a technical level, identification of standards to design and test to is located within the SEMP, along with the relevant requirements documents and SOWs generated in the Legislative stage. However, abiding to a set of guidelines for the design process of space systems is also a major concern for projects. Considering the main players in the Western world on a space systems level, there are three main sets of standards to consider in these regards. International Organisation for Standardisation (ISO) standards, which includes space and general use engineering standards for international use, European Cooperation for Space Standardisation (ECSS), which is adopted by the ESA and NASA Procedural Requirement (NPR) which are NASA requirements and thus are followed by a significant number of projects.

For maximum organisational and governing body compatibility, the Tiv-Model should follow, or at least be compatible, with the adoption of one or more of these standards. This consideration was already planned for, as the Tiv-Model borrows a lot it’s structure from NASA’s and AIAA’s system engineering life cycles, which adopt these standards. These standards overlap in many ways, and their differences are slight and specific to the intention of their creation. It is outside the scope of this thesis to analyse these standards any further.

Many of these requirements overlap or are very similar in critical ways, making much of the documentation interchangeable. In addition to this, many of the requirements specify aspects to be done within a certain task, i.e. the SEMP. Tiv-Model’s goal-based engineering format means that, so long as the deliverable is met, any of these standards can be implemented as the method. For instance, ECSS-E-ST-10-02C is about Verification of design and specifies that there should be separate verification activities for qualification and acceptance, as well as reviews for aspects that can only be proven after launch, such as in-orbit. These are gated activities that are represented by reviews in the Tiv-Model at the end of the Amalgamative stage.

It should also be noted that some requirements of these standards are imposed upon the organisation rather than the methodology, in cases like this, the adoptability of the standards are dependent on the organisation performing the project.

Model Based Engineering

One of the participants brought up a concept called "Model Based Engineering" (MBE); this was a new term to the author. Model Based Engineering, and Model Based Systems Engineering (MBSE) are design processes that rely heavily on the use of modelling to establish and verify system requirements as well as facilitate the design process. (Long & Scott, 2011) It encourages use of parametric modelling and automation of data to ensure that tasks that engineers work on are useful contributions to the design. Design baselines are modelled and expanded upon early in the design process, and evaluation is performed through analysis, iteratively, before production of items begins. In addition, models are used for softer organisational or project concepts, such as cost or reliability models in addition to CAD models.

In this sense, the Tiv-Model is a MBSE process, although not in entirety. Although one of the main drivers of the novelty of the model is Multi-perspective modelling, this is the only required modelling aspect of the design methodology. As the function of the Tiv-Model is to leave method up to the organisation, enforcing model-based engineering is a pointless task. Instead, the Tiv-Model is adaptable to this approach.

7.5 Chapter 7 Summary

This chapter covered the focus group study component of the Tiv-Model research, including the goals, setup, results, and actions spawned from the study.

The focus group study itself involved the attendance of 7 participants, each a veteran in the space systems industry. They were introduced to the Tiv-Model and were asked how they felt about certain aspects of the model over a two-hour focus group session. Participants were also encouraged to ask questions for themselves.

There were several observations to take away from the session, primarily the perception from the participants that the Tiv-Model lacked critical information for them to be able to make generalisations about it. Other observations included that there was uncertainty about the applicability of the model in certain situations, who within an organisation would be responsible for implementing the model and a few considerations that were missed in the design of the model.

As a result, the Tiv-Model changed drastically in the final revision. Major changes included adopting a more detailed high-level model, changing the stage and deliverable structure as well as introducing V-Model like design verification feedback. Iteration and modularity options were also made more visible in the model.

With the feedback given by the focus group, the Tiv-Model had reached its final design, improved over the course of each study to a point where both the theory and execution of the model meet and address the needs of the end users.

The work to this point has culminated in an “ultimate” Tiv-Model design. In the final chapter, this process is revisited, discussing the findings as well as the pitfalls of the thesis execution and how this work could be improved.

Chapter 8

Summary, conclusions, and further work

This final chapter summarises the entirety of the work, discusses the findings and how these may be improved.

In this chapter:

- **Discussion on the thesis findings**
- **Conclusive statement on Tiv-Model**
- **Improvements to be made**
- **Potential next steps on work**

8.1 Discussion of findings

Following on from the previous two chapter's journey of verifying and validating the Tiv-Model, the aim of this section is to discuss the implications of the findings, to summarise the thoughts on the matter and to clarify any conclusions or missteps.

Firstly, the comparative study results were discussed, followed by the validation of the Tiv-Model in the focus group study, and how these steps were crucial in the work. Next, methods on how design methodologies can be continuously improved are discussed, and then followed up by V&V techniques for methodology evaluation. The final topic in this section produces some general guidance on how future engineering methodologies should be developed.

8.1.1 Evaluation of Tiv-Model

Evaluation of the Tiv-Model happened in two distinct efforts. Firstly, a comparative study verifying the Tiv-Model against the V-Model to satisfy the 5th step of the V-Square. Secondly, a focus group study of the Tiv-Model to validate the Tiv-Model by subjecting it to the scrutiny of industry veterans, so satisfy the final step of the V-Square. This section will overview the key findings from each of those studies.

At the end of the comparative study, it was found that students' opinions on the methodology varied across the groups, changing with each passing year and each iteration of the teaching plan and methodology. The aim was to teach Tiv-Model and V-Model at equal depth and in a similar manner, each with their own equivalencies represented in the "macro/mid/micro" level system adopted. Through this, method of teaching could be ruled out as a significant variable. Although changes were made to the teaching plan each year, this was to improve the quality across both methodologies. The feelings of the students on their selected methodology were compared based on how they answered the feedback survey provided.

Efficiency

Q1, 8, 12, 13

In the first case study phase, Tiv-Model users found the methodology more difficult to use than V-Model users, and some students believed that using either model would be a difficult way of performing mechatronic design. This initial inconsistency was attributed to the teaching plan, which was generally insufficient for providing useful examples using the model. This meant that the students relied on their existing knowledge, V-Model was widely taught as a design process model and thus had an advantage in this sense. This knowledge advantage was removed in subsequent years when the teaching plan was improved to provide examples of use, mitigating the perceived difficulty barrier. When the difficulty barrier was removed, the efficiency in undertaking the task was increased by reducing the effort required to perform that task.

In the first iteration of the benchmark study, it was apparent that perceived difficulty was higher using Tiv-Model. In the second, it became roughly equivalent to the V-Model in difficulty, followed by the last iteration where Tiv-Model was perceived as easier. In general, however, the perceived effort to implement across both models decreased through all three phases. Although difficulty was reduced in the Tiv-Model, there was some uncertainty from the students, as it may still have a disadvantage against traditional methods. The wording of the questions may have accounted for this uncertainty, as it did not give a frame of reference for the students to compare their experience, nor would it be expected of these students to have deep engineering design experience. Again, this was seen in questions 12 and 13, where the questions assume students have a frame of reference to describe how difficult mechatronic or complex systems design is. Additionally, these two questions carried some redundancy, therefore, the most reliable measurements taken in the study were from the first question, where “difficult” is relative to the user’s direct experience with the methodology.

Effectiveness

Q9, 19, 21, 22, 23

Across the three benchmark study iterations, the perceived effectiveness of the two models maintained a matched result; students tended towards believing the models were somewhat effective as a solution to the development of mechatronic systems, according to question 9. The perceived usefulness was derived directly from question 19, students felt that both models were moderately useful, with equal standing. This was until the final phase, where Tiv-Model’s usefulness was perceived as being much greater than that of V-Model’s.

Comparative data was not visible for the usefulness of the three levels of each model until phase 2, as this was not included in the questionnaire until then. The Tiv-Model's macro-level was rated considerably higher in usefulness than the V-Model equivalent. The micro-level of both models had mixed views, and neither were observed being used by the students in their projects. The mid-levels were roughly equal in perceived usefulness, as both models used them as an integral part of their operation.

Learnability

Q4, 15

As the phases went on, the learnability of the models generally increased. Users of both models in the later phases were agreeing that the rules were easy to understand, with Tiv-Model coming out on top in phase 3. Question 15 gave excellent insight into the user's feelings on ease of learning. From the results of phase 1 it seemed as though both models were moderately easy to learn. However, as the lesson plan changed, students were learning both models more effectively at the cost of ease of learning. Perhaps the initial phase results were an anomaly, manifesting from overconfidence from those who had mistakenly thought they had learned everything about the model. it is likely that the introduction of more rigorous teaching standard for the models accounts for the fall in in "ease of learning". Regardless, the students were more effective at applying both methodologies in the second and third phases rather than the first. This suggests that students in the first phase were given a false representation of both models. Of either model, Tiv-Model appeared the easiest to learn as represented in phase 3's results.

Applicability

Q5, 11

The perceived suitability of the two models with respect to design engineering were measured in question 5 of the feedback survey. Tiv-Model was considered generally more applicable to the problem area than V-Model, which matches predictions made in the literature review. Students felt strongly about this aspect in the third phase most of all. The difficulty of applying the model to the project was also taken as a measure of applicability. From question 11 it was seen that V-Model and Tiv-Model were rated as being similarly applicable for the first few phases, until the third phase where Tiv-Model users found it less difficult to apply. The conclusion reached was that Tiv-Model was generally more suitable for the given application. There were some reservations about the final phase which had one anomalous piece of data that shifted the trend in this manner (one student’s strong agreement to the statement shifted the V-Model agreeableness value and changed the overall rating from previous trends).

Flexibility

Q7, 20

The students felt similarly about the flexibility of both models; question 7 deals with the limitations imposed upon the students. The students were uncertain about the amount of flexibility they were given, perhaps due to limited knowledge on design methods, or previous experience of designing in such a manner. Students were split on their opinions of the limitations imposed upon them methodologically. Question 20 measured the student’s perception of freedom when it came to design decisions, in all phases the students felt uncertain again, but tended towards feeling free to making design decisions freely most of the time with both models.

Comprehensibility

Q6, 10, 16 ,18

It was desirable to measure the students understanding of the model and how their existing understanding of the design world played a part in the application of the methodology. In question 6, students were asked about their existing knowledge and how well it worked with the model given to them. V-Model user results remained consistent in their opinion over the three phases. Changes made to Tiv-Model during that time improved these results significantly, in phase three the students felt as if the Tiv-Model was more suitable to their existing knowledge than students using the V-Model. Their confidence in application of the model was measured in question 10, where both models had similar results until the final phase. Tiv-Model users reported feeling more confident in their application of the methodology than V-Model users. Question 16 queried the users about the information presented in the teaching module and the handout materials given to supplement teaching. Users of both models felt their models were well presented, especially after phase one, where a lot of visual overhaul happened on the teaching materials. Tiv-Model benefited from this the most in phase three, where there was increased frequency of users reporting that the information was better presented than V-Model. The complexity of following the methodology was investigated in question 18. Perceived complexity of the methodologies was rated similar in the first two phases. In phase three, Tiv-Model users reported lower difficulty compared to V-Model users. Through these questions it could be justified that the comprehensibility of Tiv-Model was in general greater than that of V-Model.

Problem specificity

Q2

Both V-Model and Tiv-Model users deemed their models suitable for mechatronic systems development in question 2. Students rated both methodologies as being suitable for work in this field, with Tiv-Model considered to be significantly more suitable than V-Model in phase three.

Repeatability

Q17

Repeatability was partially validated by the recurrent use of two methodologies across many samples with similar results. However, perceived repeatability is a measure of usefulness, which was measured with question 17. There was no difference in the perceived repeatability of Tiv-Model against V-Model. All students were generally accepting of re-using the Tiv-Model but were not particularly inclined more-so than the V-Model.

Competitiveness

Q3

The student’s take on the competitiveness of their chosen model was measured in relation to another model, this time against Pugh’s TDM, a model the students will have used previously and were accustomed to. Although the use of the two models was different, the students were asked about their relative experience with them. The students did not appear to be significantly more enthusiastic about using either model over Pugh’s TDM, but in hindsight this was an unsuitable question to ask. Although V-Model is comparable to TDM, Tiv-Model is only moderately comparable in terms of general process.

Reliability

Q14

The students were asked to determine whether their chosen methodology allows the clear and concise communication of concepts, either design concepts or ideas for procedures. It was found that, indeed, the students thought more favourably towards Tiv-Model when it came to communication of concepts. This was the intended effect of ensuring planning transparency was built into Tiv-Model.

Comparative study results

By the final iteration of the benchmark study, 13 of the 24 questions students were asked showed a 95% or higher confidence rate (via t-test) in the Tiv-Model being considered better than V-Model in those aspects. This was considered key verification evidence, proving that if the Tiv-Model was at least as good as, if not better than, an established and recognised design methodology (V-Model) in the same problem space, then Tiv-Model can be considered verified with respect to that intended problem.

Focus group

Following on from the benchmark study, the focus group study was carried out. This brought 7 space systems industry veterans together to learn about and comment on the Tiv-Model and what they thought of it.

Lack of information available

The focus group participants were keen to learn more about the Tiv-Model outside of the presentation given to them, asking a host of questions about the inner workings of the model in a level of detail greater than that presented to them. Although this was encouraging, it was apparent that the information presented to them was not enough for them to come to some of the conclusions the focus group was designed to get answers to. Instead, the primary conclusion, after discussion with the participants, was that the information displayed and on offer on the surface of the Tiv-Model was not enough to demonstrate its inner workings or principles. This key observation was followed by suggestions on how the model could be improved to accommodate that information.

Application of the Tiv-Model

Another conclusion from the focus group was that it did not seem clear who was responsible for the use and implementation of the model within an organisation. The applicable scenarios that the model could be used in were also discussed, with the participants concluding that the linearity of the model may hinder it in more complex scenarios.

Perceived benefits of the Tiv-Model

Other than the critical feedback given with respect to the Tiv-Model, it also received reinforcing feedback. The participants agreed that the Tiv-Model was likely to aid in the improvement of product quality because of its implementation. They also stipulated that it may be highly beneficial to systems engineers and project managers in the long run.

Through these studies, notes were being taken for continuous adjustment of the model based on participant feedback. In the next section, the means of continuous improvement of the Tiv-Model was discussed to establish how this was performed over the course of the studies and what improvements were made in that process.

8.1.2 Continuous improvement and evolution of Tiv-Model

Part of the purpose of benchmark studies were to establish the perceived effectiveness of Tiv-Model and compare it to the V-Model. The function of iterative studies here was to use the lessons learnt from the previous phase to improve the Tiv-Model. Information was collected from each iteration and adjustments were made to improve the effectiveness of the model, the teaching practices, and the data collection process.

Teaching improvements

Before the initial methodology trials, a formalised teaching plan was not constructed. Instead, given the short notice of the study opportunity, the graphics and written formalisation of the principles were the only references that could be used. This accommodated study on the high-level functionality of the Tiv-Model, but lacked the theoretical detail. This detail would be present in the research materials as part of this thesis. Hypothetically, teaching the students the research on the whole could be effective, but inefficient, as it would not work in a crowded class environment. It was recognised that the depth of knowledge being presented would require a teaching change.

From benchmarking study phase 1 onwards, a teaching plan was set up to convey the working principles of both Tiv and V-Models to students and allow them to apply this information meaningfully to their group assignment. The information and its delivery were designed around the student projects. The initial teaching plan was:

- An initial brief lecture on the design process, design methodology and method principles
    - This was to ensure that all students were up to speed on foundational knowledge of design. It served as a mitigating factor for students who had little formal design education, and a refresher for those who experienced it in previous years but needed grounding in terminology and other aspects.
- A lecture on the basic principles of Tiv-Model and the benchmark model, V-Model
    - This lecture introduced the concepts of macro, mid and micro level methodology and how these elements tied together. The working principles of each model were presented, explaining where the models are unique and where they are similar. Parallels were drawn to the previous lecture's materials and, where applicable, the previous experience of the students. In doing so, students were provided with a frame of reference for understanding the concepts being taught.
- Handing out reading materials for Tiv-Model and V-Model
    - The materials were in the form of printed documents, several per group, showing some of the key elements of either model with brief refresher explanations.
- Continuous support through direct student interaction
    - Visiting the class later down the line of the project to catch up with progress and to answer any questions proved beneficial to the students understanding, along with email support. Student contact was limited due to constraints in the class timetable.

This teaching plan was limited by contact with the students, given that the lectures took place during regular class time. Thus, interaction with the students was less than desired, nor could the amount of methodological study they conducted for this subject be controlled. The initial result was that students were generally not receptive to the concepts of either model, and they often misunderstood some of the principles and their implementation. Students had informally brought up that the lack of direct guidance had affected their perception of usefulness in the model. It was not surprising that this was reflected in the survey findings; students in Phase 1 were less confident in application and less agreeable when it came to matters of efficiency or effort in application. Consequently, a more practical approach was implemented starting in phase 2 to solidify teaching. Added to the program was:

- A workshop designed to teach the mid-level operation of both models
    - After the second lecture, students were given a hands-on workshop to teach them basic operation of the methodologies. To save time and effort, only the methodology that the students chose were given to them on a group-by-group basis. Students were asked to plan out a small selection of tasks using the methodology as a guide. This aimed to show the students how to plan their project out using the methodology. The students described the subtasks, the deliverable expected of the subtask, and a protocol outlining how to achieve the deliverable. Students were also asked to perform the protocol that they had chosen to achieve the deliverable, this was to highlight the usefulness of foresight and planning in the early stages. This part was cut in Phase 3 due to time limitations with the students.
- Refined lecture material
    - Areas of the lecture material that students were having a hard time with understanding were clarified. Clarification, simplification of concepts and use of examples were three major changes. Clear definition of terminology was another change, as well as a more concise look at the different levels of each methodology, including updated graphics.
- A new set of hand-outs with more detailed breakdowns and usage notes
    - The new hand-outs consisted of two documents for each model, both in physical and digital format. The first document contained a step-by-step implementation guide for the methodology in question, showing the student how to implement,

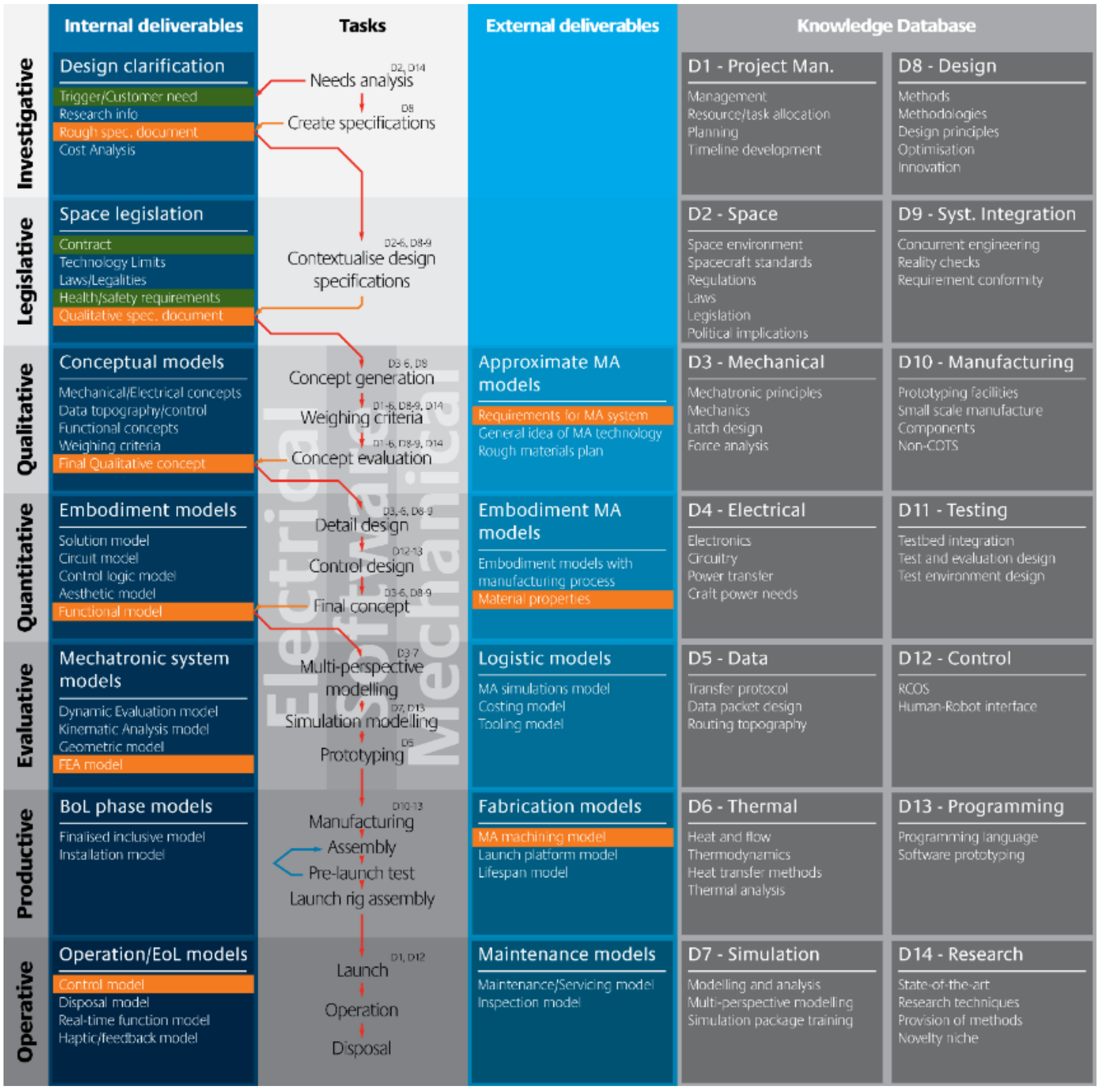
    plan and carry out work with the methodology. The second document had a breakdown of the anatomy of each model in detail, describing terminology, concepts, and structures within the methodology.

- Improved continuous support through sit-in sessions
    - Adding to the previous support, sit-ins were conducted during group discussion times, where students present their progress, ask and answer questions about the project and voice their concerns. The class was also visited outside of these sessions and student presentations were attended. This helped gain an informal insight on student concerns and progress and allowed them to receive clarification when needed, particularly regarding interaction with the methodology.

Through these improvements in the education of the methodology, the best balance of student understanding and time consumption/resource expenditure was sought for in the teaching plan. Notable increases in information retention and understanding were achieved in later groups of students due to the inclusion of the workshop and refined teaching materials. The benefit of this was visible in the student surveys, where positive opinion was improved across all factors of methodological interaction. In some cases, in phase 2, however, it was observed that the introduction of new information into the teaching environment did not meld as well as originally intended. New information, such as the introduction of Tiv-Model's mid-level inner workings, reduced the confidence that the students had in the model as the information presentation was perhaps too complex. Through an additional set of changes, this and other pieces of overly complex information were eliminated for a simple and streamlined approach. Presentation simplicity and referencing prior experience was found to help the students understand the new knowledge.

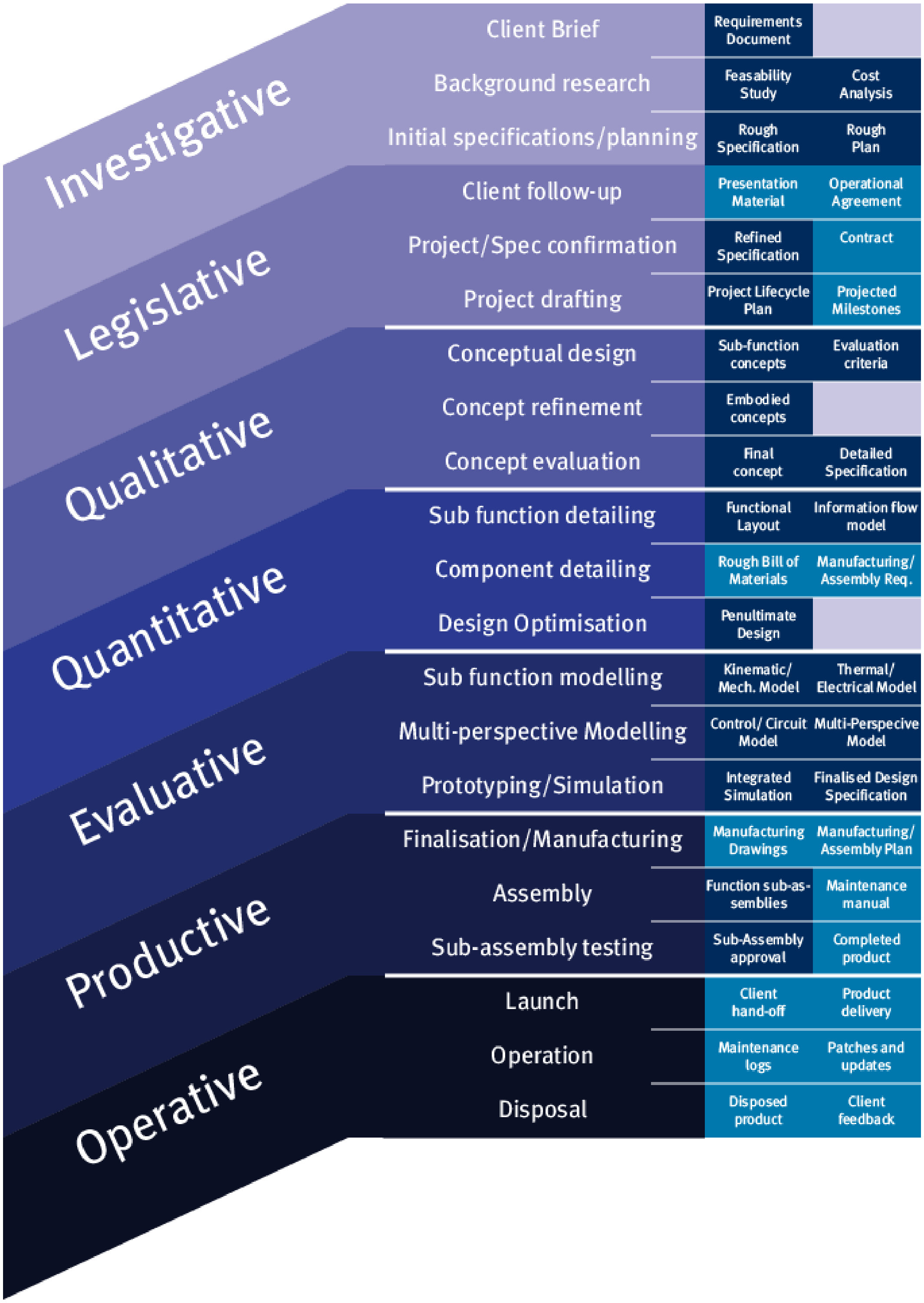
Model improvements

Over the course of the three survey phases, the opportunity was taken between semesters to adjust the Tiv-Model in addition to how its information was presented. To begin with, only the macro-level was being presented to students, with parts of the mid-level present but evolving. It began with a modest but informationally heavy visual approach for the first variation of Tiv-Model, shown in Figure 8-1. Attempts were made to capture as much information as possible in this iteration, but interactions with the class and student feedback proved that overloading the information in one graph was not a suitable tactic for learning. As a result, the tiered "level" system, seen present in other methodology learning strategies, was followed. The Tiv-Model was changed over several iterations to present a simplified version of the macro-level only, and the mid and micro-levels are represented separately. The 2nd macro-level variant for Tiv-Model is represented in Figure 8-2. The penultimate version of the model is shown in Figure 8-3, which followed the final comparative study and included all feedback and improvements until that point.



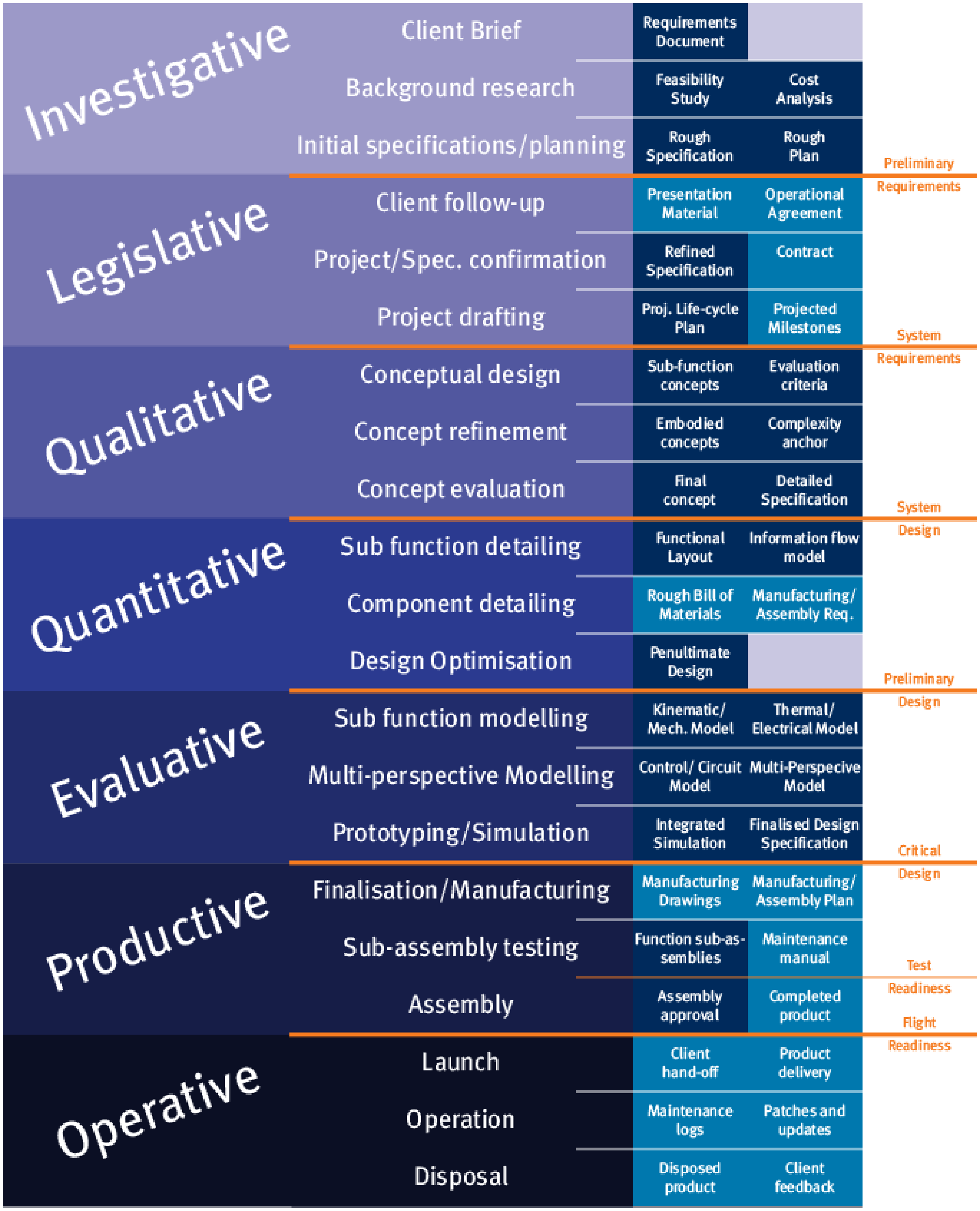
	Internal deliverables	Tasks	External deliverables	Knowledge Database	
Investigative	Design clarification Trigger/Customer need Research info Rough spec. document Cost Analysis	D2, D14 Needs analysis D8 Create specifications		D1 - Project Man. Management Resource/task allocation Planning Timeline development	D8 - Design Methods Methodologies Design principles Optimisation Innovation
Legislative	Space legislation Contract Technology Limits Laws/Legalities Health/safety requirements Qualitative spec. document	D2-6, D8-9 Contextualise design specifications		D2 - Space Space environment Spacecraft standards Regulations Laws Legislation Political implications	D9 - Syst. Integration Concurrent engineering Reality checks Requirement conformity
Qualitative	Conceptual models Mechanical/Electrical concepts Data topography/control Functional concepts Weighing criteria Final Qualitative concept	D3 6, D8 Concept generation D1-6, D8-9, D14 Weighing criteria D1-6, D8-9, D14 Concept evaluation	Approximate MA models Requirements for MA system General idea of MA technology Rough materials plan	D3 - Mechanical Mechatronic principles Mechanics Latch design Force analysis	D10 - Manufacturing Prototyping facilities Small scale manufacture Components Non-COTS
Quantitative	Embodiment models Solution model Circuit model Control logic model Aesthetic model Functional model	D3,-6, D8-9 Detail design D12-13 Control design D3-6, D8-9 Final concept	Embodiment MA models Embodiment models with manufacturing process Material properties	D4 - Electrical Electronics Circuitry Power transfer Craft power needs	D11 - Testing Testbed integration Test and evaluation design Test environment design
Evaluative	Mechatronic system models Dynamic Evaluation model Kinematic Analysis model Geometric model FEA model	D3-7 Multi-perspective modelling D7, D13 Simulation modelling D5 Prototyping	Logistic models MA simulations model Costing model Tooling model	D5 - Data Transfer protocol Data packet design Routing topography	D12 - Control RCOS Human-Robot interface
Productive	BoL phase models Finalised inclusive model Installation model	D10-13 Manufacturing Assembly Pre-launch test Launch rig assembly	Fabrication models MA machining model Launch platform model Lifespan model	D6 - Thermal Heat and flow Thermodynamics Heat transfer methods Thermal analysis	D13 - Programming Programming language Software prototyping
Operative	Operation/EoL models Control model Disposal model Real-time function model Haptic/feedback model	D1, D12 Launch Operation Disposal	Maintenance models Maintenance/Servicing model Inspection model	D7 - Simulation Modelling and analysis Multi-perspective modelling Simulation package training	D14 - Research State-of-the-art Research techniques Provision of methods Novelty niche

Figure 8-1 - Tiv-Model v1 (sub variant for space mechanical interface)



Investigative	Client Brief	Requirements Document	
	Background research	Feasability Study	Cost Analysis
	Initial specifications/planning	Rough Specification	Rough Plan
Legislative	Client follow-up	Presentation Material	Operational Agreement
	Project/Spec confirmation	Refined Specification	Contract
	Project drafting	Project Lifecycle Plan	Projected Milestones
Qualitative	Conceptual design	Sub-function concepts	Evaluation criteria
	Concept refinement	Embodied concepts	
	Concept evaluation	Final concept	Detailed Specification
Quantitative	Sub function detailing	Functional Layout	Information flow model
	Component detailing	Rough Bill of Materials	Manufacturing/ Assembly Req.
	Design Optimisation	Penultimate Design	
Evaluative	Sub function modelling	Kinematic/ Mech. Model	Thermal/ Electrical Model
	Multi-perspective Modelling	Control/ Circuit Model	Multi-Perspecive Model
	Prototyping/Simulation	Integrated Simulation	Finalised Design Specification
Productive	Finalisation/Manufacturing	Manufacturing Drawings	Manufacturing/ Assembly Plan
	Assembly	Function sub-assemblies	Maintenance manual
	Sub-assembly testing	Sub-Assembly approval	Completed product
Operative	Launch	Client hand-off	Product delivery
	Operation	Maintenance logs	Patches and updates
	Disposal	Disposed product	Client feedback

Figure 8-2 – Tiv-Model v2



Investigative	Client Brief	Requirements Document		
	Background research	Feasibility Study	Cost Analysis	
	Initial specifications/planning	Rough Specification	Rough Plan	Preliminary Requirements
Legislative	Client follow-up	Presentation Material	Operational Agreement	
	Project/Spec. confirmation	Refined Specification	Contract	
	Project drafting	Proj. Life-cycle Plan	Projected Milestones	System Requirements
Qualitative	Conceptual design	Sub-function concepts	Evaluation criteria	
	Concept refinement	Embodied concepts	Complexity anchor	
	Concept evaluation	Final concept	Detailed Specification	System Design
Quantitative	Sub function detailing	Functional Layout	Information flow model	
	Component detailing	Rough Bill of Materials	Manufacturing/ Assembly Req.	
	Design Optimisation	Penultimate Design		Preliminary Design
Evaluative	Sub function modelling	Kinematic/ Mech. Model	Thermal/ Electrical Model	
	Multi-perspective Modelling	Control/ Circuit Model	Multi-Perspecive Model	
	Prototyping/Simulation	Integrated Simulation	Finalised Design Specification	Critical Design
Productive	Finalisation/Manufacturing	Manufacturing Drawings	Manufacturing/ Assembly Plan	
	Sub-assembly testing	Function sub-assemblies	Maintenance manual	Test Readiness
	Assembly	Assembly approval	Completed product	Flight Readiness
Operative	Launch	Client hand-off	Product delivery	
	Operation	Maintenance logs	Patches and updates	
	Disposal	Disposed product	Client feedback	

Figure 8-3 – Tiv-Model v3

Some key changes made to the methodology over this time span were as follows:

- Simplification of diagram information
- Simplification of chronological task plan
- Introduction of recognised aerospace milestones
- Other aesthetic changes
- Implementation of separate knowledge databases diagram
- Development of separate mid-level model
- Selection of separate micro-level model
- Optimisations in the task plan text

Although some changes affected the operation of the model at this stage, most were visual. This was in direct response to the student feedback, many claiming that, initially, the model looked overwhelming.

Validation of model

The final changes made to the model were made after the focus group study, where industry veterans would critique and offer feedback on the model. None of the core concepts were challenges by the focus group, but the group felt that the amount of information they were given was incomplete. The primary conclusion from that group was that the information on display was too simplistic to offer depth, and that the macro-level model does not reveal much in the way of detail.

To address this, the focus group feedback was added to the model, resulting in the biggest visual change in the model, including further emphasis on the workflow, showing the verification stage in greater detail. The types of deliverables were changed, but the core constructs of the model were untouched. The model was flipped on its side and the y-axis showed the system level of work carried out at each stage. This change in part was made to give the Tiv-Model more of the information that the focus group participants needed to see, but also to give the model a novel visual style. The model now looks like the letters “TIV”, which should reinforce the structure to those who use the model. This final version of the model is shown in Figure 1-1.

Data collection

It was noted that during the comparative study, data collection was an important consideration for continuous improvement. However, because the aim was to see gradual change in each of the results, and that this realisation was made too late, many of the desirable changes to be made to data collection were not made. These changes are discussed in 8.2.

The iterative nature of the back-to-back studies meant that the Tiv-Model seen gradual improvement over the course of the thesis, with each study giving something to the model, until the final validation step solidified the construction of the model and focused on the presentation of information. Verification and validation of the model was done through V-Square, a 6-step technique to validating design methods, which is elaborated on in the next section.

8.1.3 Verification and Validation methodology

At the beginning of the research, design methodology validation techniques were of great interest. It was recognised that some of the tools used to evaluate design methods could be repurposed for use with design methodologies, due to the common structuring between them discussed in section 2.2. The justifications made in defence of using V-Square as a validation tool relied on methods and methodologies having similar internal structures. It was concluded that they do indeed share common functional components and processes, although the key differences are in the scaling.

Of the several evaluative tool candidates witnessed, V-Square was chosen. Analysis of V-Square showed that the tool was very useful for this situation. It provided a very lean and vague boundary of definition that allowed validation of methods and methodologies, as well as other design tools, across any discipline. V-Square was flexible; therefore, it was an ideal candidate to recommend to others wishing to validate their own models. The use of V-Square was also partially based on its self-validating nature, which can be confirmed using traditional simple logical leaps. The simplicity and intuitiveness of the tool itself also aided this decision. V-Square included recommendations for its use, which is inherently helpful and accompanies the teaching-focus of the package of knowledge prepared in this thesis.

The aim of this research was to deliver satisfactory means to the verification and validation question. Robustness of the findings was increased by adopting ideas taken from medical science. Medicine's robust set of testing standards are excellent when working with quantities and large population sizes. However, since the goal was to develop robustness for use in a design related environment then adjustments had to be made. Section 2.6.3 outlines how objective metrics used in medicine are linked to equivalent design metrics, and thus measure the effectiveness of a methodology in a similar, quantitative manner. In Chapter 4, these elements are linked together into the combined Requirements document used to design Tiv-Model. Chapter 6 discusses the use of these metrics to judge both models in an empirical manner. Due to time constraints on the survey design, this was not achievable. A survey that tests for all the medical metrics proposed was not successfully created, however a survey that checks for the other metrics found in literature was still achieved.

The Tiv-Model teaching materials and strategy devised in the thesis was deemed adequate, although there were many limitations brought on by the academic environment of the comparative study. There are some recommendations to be made to improve the evaluation strategy for any following studies, which the remainder of this section will cover.

Perfect case study situations would involve design companies participating in mock, or even real, design projects that utilise the new model. In this kind of test environment, the model's implementation strategy, employee training and utilisation of designer freedom comes into play. This would be ideal, but financial risk must be accepted as a downside for something on this scale. In academic environments this risk is not present but replaced with the risk of teaching false or incorrect information to students and hampering their education. Therefore, the Tiv-Model study comparative study was embedded in an existing design project that was compatible with it, as per the suggestion of V-Square. Considerations were made for the kind of project and how relevant it is to students and staff.

With regards to the method used to gather data on the two models, the survey strategy was found to be adequate for obtaining useful data on a large scale. On a smaller scale, one-to-one interviews would be ideal to gather detailed information about aspects of the models. This would be particularly useful when fine-tuning the Tiv-Model as the input would be more focused on the finer details. These interviews were be structured around a short teaching experience that focused on the model to be evaluated. This should be presented to the evaluators with physical handouts and followed by discussion of concepts before a formal critique. Group sessions should be encouraged for maximising efficiency and gathering more robust peer-validated results.

Questions used in a survey should be thoroughly premeditated to generate information that compliments the needs of the hypothesis. It is recommended that the questions should correlate to the categories within the Methodology Requirements Document, or the requirements presented for design methodologies, so that comparisons can be made. In this thesis, the lack of consideration given to these questions, and not changing them when the opportunity was given had resulted in redundant and missing information that would have otherwise been useful. The decision was made to keep the questions so that future phases would at least have comparable results. The faults in the thesis were covered in more detail in section 8.2.1.

8.1.4 Guidance on design methodology development and validation

With regards to this thesis, when using it as a guide for the design and validation of design models, this work could be used as a rough template to follow. However, it is acknowledged that there is no one true method. Improvements on this process are a net benefit to all research in this field, and to engineering design as a discipline. Researchers are encouraged to follow recommendations from the V-Square plan, but an alternative bullet point list of considerations for model development and validation are as follows:

- Perform preliminary research into the field of interest, particularly in existing methodologies.
- Use the PDS structure to generate requirements for the methodology, including unique aspects or niche elements of the model.
- Decide which requirements are most important, weigh them.
- Use structuring techniques and design theory shown to create the methodology conceptually, ensure that each of the structural elements serves some purpose.

- Ensure that all requirements are met to a satisfactory degree, reality check this by structured means and justification.
- Work the details into a presentable graphic format for others to understand, develop teaching materials in the same way.
- Devise an experiment plan that involves returned feedback from multiple users. Students, designers, and other experts are encouraged, laymen should be avoided. The number of participants should dictate the nature of the study, interview, individual case study or survey.
- Select a methodology that is near peer to the created one and have this act as the benchmark for testing. Learn and understand this methodology, aim to teach the benchmark in the same manner and depth as the newly developed methodology.
- Construct questions for the participants that answer the frame of “does this methodology satisfy the intended requirement?”. Remove redundant questions, cover as many aspects of the methodology as possible.
- Embed means for data collection and analysis within the test plan, be aware of limitations of the data collection (question limit, for example).
- Perform an integrated session, or series of sessions with the target group through teaching, feedback, and data collection. A “reality check” session on the first pass will help clear up preliminary issues.
- With feedback given, the goal of each data collection phase should be on improving the model, data collection and teaching process. Refinements should be constructive and continuous, the number of phases needed is not given but limited on convenience, time, cost etc.
- Use the data collected to justify decisions and results, empiricism is a powerful tool when analysing many results.
- Finalisation of the methodology should also bring to light links between it, the PDS and the research. Make a final validation based on the opinions of industry veterans to act as a conduit in place of an actual use case.
- Use the validation step as a final adjustment before making the logical leap to completion.

Overall, the key to this process is that methodology design follows the same path as the engineering design process, and the methodology being developed should be treated as a product in this sense. This is the advice that can be given to academics keen on using this evaluation strategy in their own plans.

8.2 Further work and improvements

In this subsection the aim was to provide some suggestions on how future work could be conducted to improve upon the results of this thesis. It would also help others use the information to improve academia and show what could have been done differently. Like most academic work, this thesis was highly experimental, thus prone to error and lacking optimisation. There were wrong turns in a few places and some corrections were not made before the mistakes happened.

8.2.1 Experimentation fidelity

The experimentation was mostly adequate besides a few critical matters, the first being the applicability of the questions in the comparative study. This component of the experiment was rushed, and not thoroughly thought out due to time constraints on the window of opportunity for the study to happen. The comparative study had to take place during the first semester of the year, leaving very little time to act. The thesis author had a misunderstanding of questionnaire and survey design principles. This meant that some questions were either left unanswered, did not match the required information needs or were redundant. The survey tool used at the time was limited to 20 questions, thus compounding the issue. This meant some useful information was missing, such as how the students perceived the usefulness of individual components and concepts within the methodology. This was later remedied by use of another in-house survey tool that was integrated with the university intranet, allowing more questions to be asked and data to be managed easily.

The second error was not using the opportunity to change the questions asked. With the new tool, more questions could be asked in the form, yet they were kept consistent across the study phases. This would be the best method to monitor development of the methodology over time, as the two results could be directly compared question-by-question. This indeed proved useful in the development of the Tiv-Model, but it hindered the validation process slightly, where further inferences had to be made based on the data. Ensuring that the questions were correct prior to the 1st iteration was key.

It also would have been beneficial to attempt to use the “lessons from medicine”, shown in section 2.6.3, as metrics for performance evaluation. Time constraints on the creation of the survey meant the testing procedure were imperfect. Hypothetically, if surveys were to be taken again the use of Table 8-1 is recommended to determine the questions being asked in this survey, along with any other information the table suggests.

Pharmaceutical Parameter	*Method evaluation context*	*Evaluation method*
Accuracy	Ability for methodology to produce designs expected of it, embedment of requirements	Examination of end-products post-testing
Precision	Ability for methodology to repeatedly reproduce designs that are expected of it, requirements embedded throughout methodology	Examination of student marks post-testing
Specificity	Projected influence that the structure of the methodology has on the end-product	Comparisons between test model and benchmark in markings/other aspects of the design evaluation
Limit of detection	Lowest amount of application from the methodology that can be considered useful	Consultation with users
Limit of quantification	Lowest amount of application from the methodology that is provably useful	Consultation with users + potential case study
Linearity	Structure showing an increase in positive influence with respect to following the methodology	Survey data + marks/examination of design quality
Range	The acceptable range of design situations the methodology is suitable for	Literature and industrial expertise
Ruggedness	Ability for methodology to repeatedly reproduce designs that are expected of it across variants of itself and amongst other design bodies	Iterative testing
Robustness	Ability for the methodology to maintain its structure with minute changes across it	Consultation with users

Table 8-1 - Medicine-based metrics for methodology evaluation

8.2.2 Tiv-Model digital web app development

Tha aim was to evaluate the Tiv-Model's ability to be integrated with computer-aided Product Lifecycle Management (PLM) tools. One of the outcomes of the literature research showed that design methods and tools must adapt with the ever-changing times, specifically when it came to the prevalence of digital tools. PLM systems have developed over time to become incredibly common in complex and mechatronic design industry. As a result, many of the basic structural elements of Tiv-Model (its linearity and Gantt-chart-like break down) are based on the author's experience with PLM systems and engineering design processes that are incorporated in those systems.

Alongside the Tiv-Model, an in-house web-app was developed that contained everything needed to setup and manage a design project using Tiv-Model. The web-app contained an editable gantt-chart overview of the Tiv-Model. The tool gives a template of the macro-level main task stages, the user then sets the timeline and subtasks within those tasks, linking sub-tasks and managing dependencies. The project management or leader also fills out the required fields in the mid-level viewer for their engineers to abide by. The system comes with document submission, management and tracking in place, so when designers finish a task, all the related digital information can be uploaded under that subtask and checked off for completion. Users can be assigned to groups, which can be broadly used to represent design teams split by discipline, component, or sub-system. Groups and users can also be assigned to subtasks, and each user knows which work they are responsible for.

This is a basic representation of a PLM system, but is very "bare bones". There was some minor time investment in this, and the web-app saw limited use. With further development of the Tiv-Model in a viable product, the in-house app development could be continued, and more advanced features added. Planned features include:

- User administrative levels
- Graphical overhaul
- Integration with folder browsing (explorer)
- Exportable table data on project, completion times, file metadata etc

- Search functionality on all aspects
- User direct messaging, email linked
- Document check-in/check-out to limit single user documents, and support for multi-user documents
- Detailed but simple customisation of macro and mid-level models
- Templates for all tasks and subtasks

8.2.3 Validation guidance and Tiv-Model instructions

One of the goals of the thesis was to aid academia as a steppingstone on the path to optimised and validated methodologies, methods and tools, and eventually optimised design. It is hoped that this thesis can be used as a “manual” of sorts for academics aiming to inform themselves on validation for their own methodological creations. Additionally, to those who would like to use the Tiv-Model and wish to implement it within an individual or group design activity, it is hoped that this documentation will suffice for recommendations. Long-term, however, the aspiration is to develop a more refined and formalised guide, much like the helpful books by Pugh on his own methodology. The publications would outline a step-by-step process that investigates implementing, teaching and using the Tiv-Model in an organisational and academic context. The same goes for the validation guide, hoped to be an independent publication in the future.

8.2.4 Loss of academic data

Due to the author’s negligence, a significant amount of data regarding studies done on the Tiv-Model were no longer usable for the thesis and could not be used to demonstrate the model’s effectiveness. This was due to non-compliance of GDPR and University Ethics policy, entirely the author’s fault. Important lessons have been learned regarding procedure and the importance of following it, and alternative data was sought out to replace the missing information. This extended the time it took to write the thesis, but ultimately strengthened its credibility.

8.3 Summary

The primary output of this thesis was the Tiv-Model, an optimised design lifecycle model for complex space systems design. It has several unique features; it incorporates much of the novel research in design theory from the past two decades, it is modular and can be adapted for almost any complex system and it has been validated by new techniques to allow better integration with industry. The initial research identified that, from an industry perspective, academic models lack validation or proof to back their written merits, and thus models are not being accepted as much as academia would like. This was a key challenge in the research, and it was decided that the validation technique should be a focus for the thesis. Academic tools and theories were used to achieve this goal, such as the Validation Square, to further promote and solidify the usefulness of academic contributions.

Requirements for design methodologies

With a strong emphasis on design theory, a list of requirements was generated based on many pieces of research about design methodologies, this was another major contribution to knowledge. Tiv-Model was designed around these requirements, following the traditional design process. Using the Validation square, an academic tool designed to validate methods, the Tiv-Model was proven to be valid and useful. The Tiv-Model was used to demonstrate a desirable design process and validation technique that can be repeated for other academic design models.

Evaluation of design methodologies

The validation process involved six main steps, as specified by the V-Square. It was accompanied by experimentation in the form of a series of individual and group design projects, as well as an expert focus group. The projects were suitable for proving the Tiv-Model's viability on an industrial scale. The individual case study provided a reality check, as well as a detailed look into the use of the methodology. The semester long group projects had students form large teams to accomplish their task, creating an environment where the planning and management aspect of the methodology could come into play. The focus group provided a validation check to ensure the final model was suitable for industry use.

The results from the multi-phased series of studies showed that this method of evaluation was practical, but time-consuming. Each iteration allowed an opportunity to improve the methodology, teaching practices or data acquisition plan. Transforming qualitative measurements into quantitative ones allowed an empirical lens to be used, reinforcing their robustness. Benchmarking against a similar methodology, V-Model, was used to gather comparative data and measure the viability of Tiv-Model against an industry standard that had already been accepted as valid.

Tiv-Model as an example and guide

Tiv-Model, although a product on its own, was also a device in this thesis used to showcase several other aspects of design methodologies. It showed the design process, the validation process, and how these items can be used in academic research as steppingstones to power efforts into making practical tools for industry. Through this process the model was improved, showing the improvement in the experimentation survey data, where in the final iteration Tiv-Model had surpassed V-Model in many ways according to the perceptions of the groups involved. The thesis acts also as a guide to the process. Recommendations are made where needed and the document shows where the process had failed, to caution others. It is hoped that in one of these areas this thesis will be useful to future work.

8.3.1 Contributions to knowledge

The novel aspects and knowledge contributions from this thesis were:

The creation of an engineering design methodology for use with space and complex systems industry

Tiv-Model was developed, a design methodology that was engineered to mitigate the negative effects of various challenges in space and CSI. This model was based on modern academic research, the majority of which forms the Methodology Requirements Document that guided the creation of the model.

The generation of a series of design guidelines for development of design methodologies

The Methodology Requirements Document is the manifestation of requirements to be used to create an engineering design methodology. Along with the set of basic requirements were a set of contextual requirements derived from the specialist subject (CSI) and a small number of recommendations for best practice. The thesis shows how to derive these requirements for future endeavours and how these requirements are linked.

The generation of a method and experiment set for verification and validation of engineering design methodologies.

Using academic research like the Validation Square, a suggested verification and validation plan was carried out as per the recommendations of the V-Square. Through a 6-step process, the Tiv-Model was verified and validated. The steps along the way were logged so that others may use it as a guiding plan.

The documentation of a guide on the creation of engineering design methodologies.

Budding model creators could use this thesis as a guideline, reference resource and justification for their design decisions when making their own model.

The Demonstrative model of Tiv-Model implemented into a digital tool

The Tiv-Model was implemented into a rough Product Lifecycle Management accessible to students via the University intranet. This tool was demonstrated by translating students’ projects into the system to show how it tracks tasks. Although not complete, the groundwork for implementing the design model into a digital tool is there.

These 5 contributions are the core deliverables of the thesis, and thus form the most important items in the text. If others draw knowledge from this thesis, it should be from one of these items.

8.3.2 Thesis visual summary

For a rapid review, a visual summary of the work done in each chapter of this thesis is laid out below from Figure 8-4 to **Error! Reference source not found.**.

In Chapter 1, the thesis was introduced in abstract form and presented to the reader in shorthand.

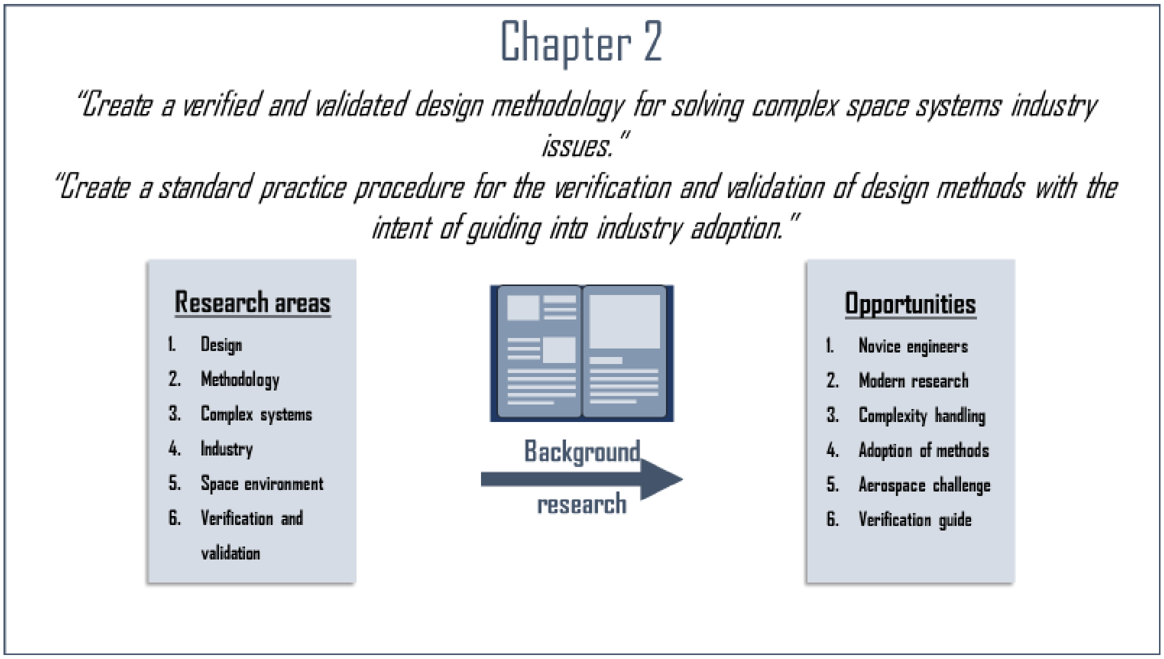


Figure 8-4 - Chapter 2 visual summary

In Chapter 2, some key literature areas were researched and opportunities for knowledge development were speculated upon. Several opportunities in each area were identified that could be solved with one stream of research effort: the development of an engineering design methodology, including guidance on the creation and validation.

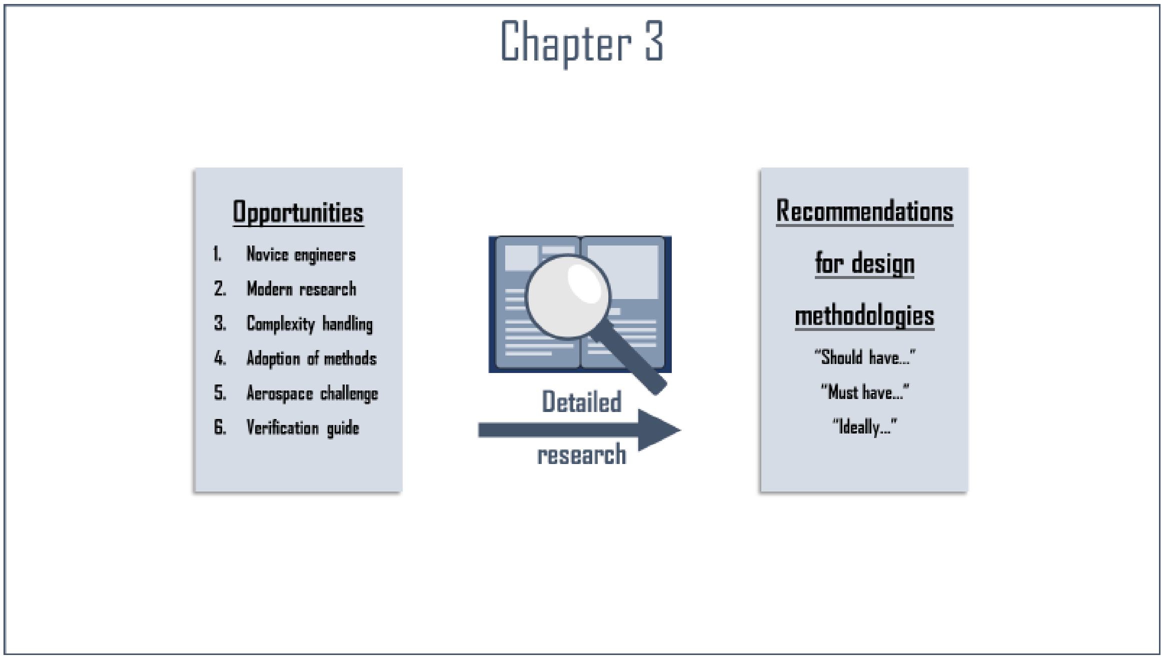


Figure 8-5 - Chapter 3 visual summary

In Chapter 3, further research was committed to the 6 key research areas to help define the problem and hypothetical solution. Key findings were made with respect to evaluating the proposed engineering design methodology solution, and the best method for creating it.

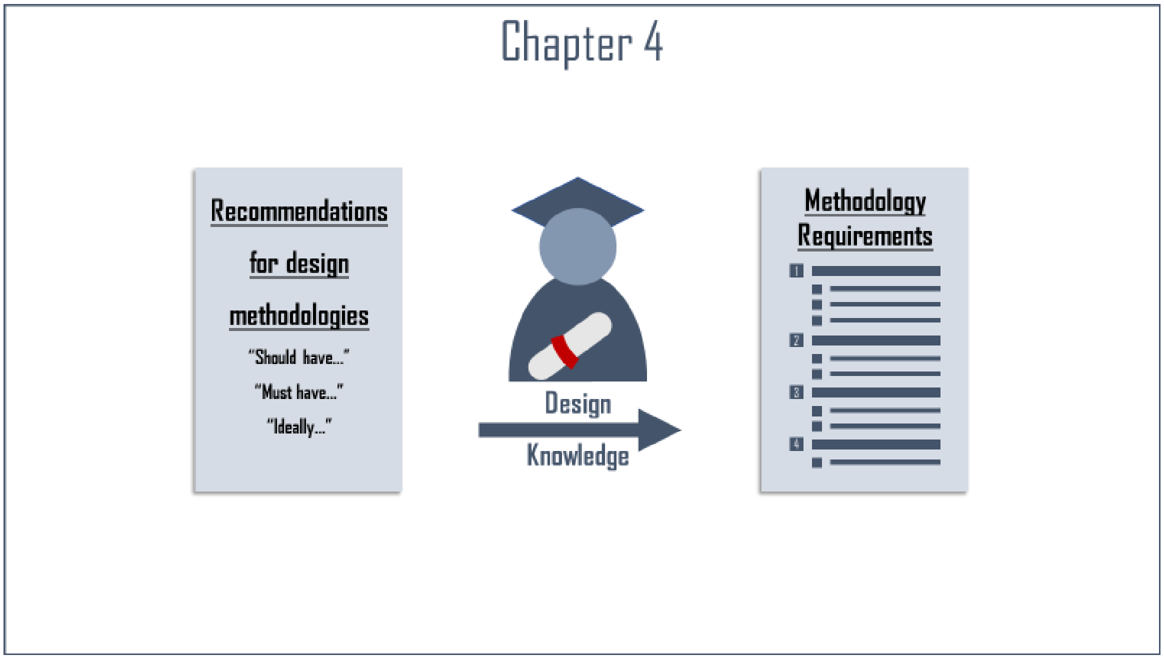


Figure 8-6 - Chapter 4 visual summary

In Chapter 4 more detail was observed regarding the development of a design methodology using the literature suggestions as requirements. Using design knowledge, these design requirements were transformed into design specifications in a formalised PDS.

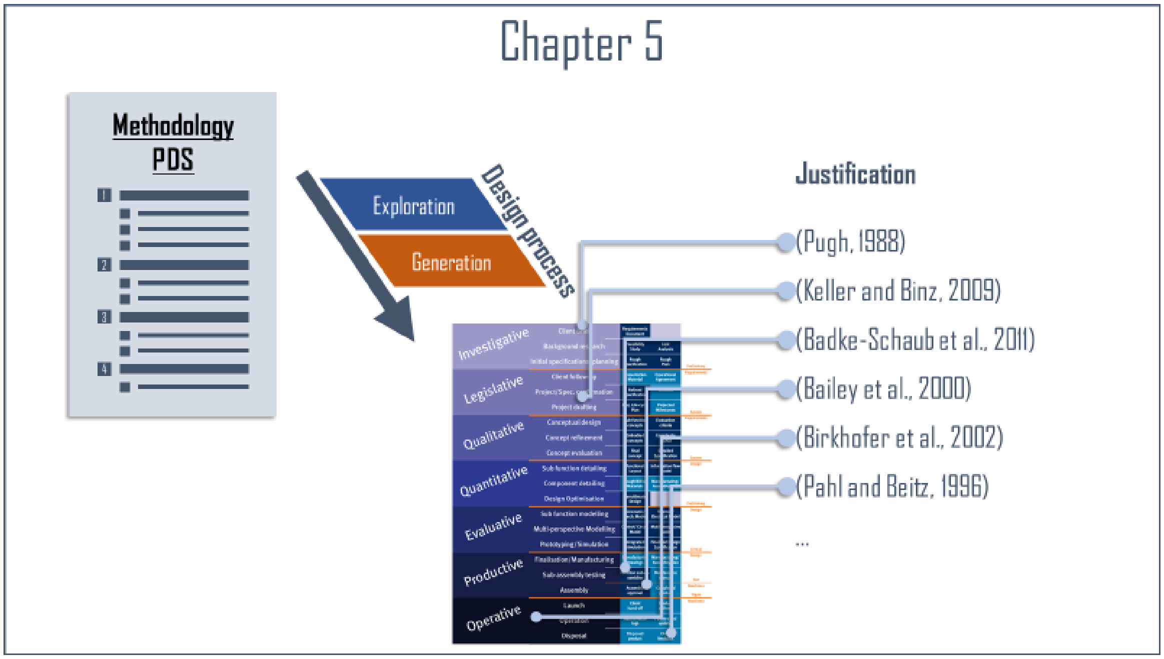


Figure 8-7 - Chapter 5 visual summary

In Chapter 5 the Tiv-Model is shown, an engineering design lifecycle developed using the PDS generated in Chapter 4. This chapter explained how Tiv-Model works and justifies the design decisions made.

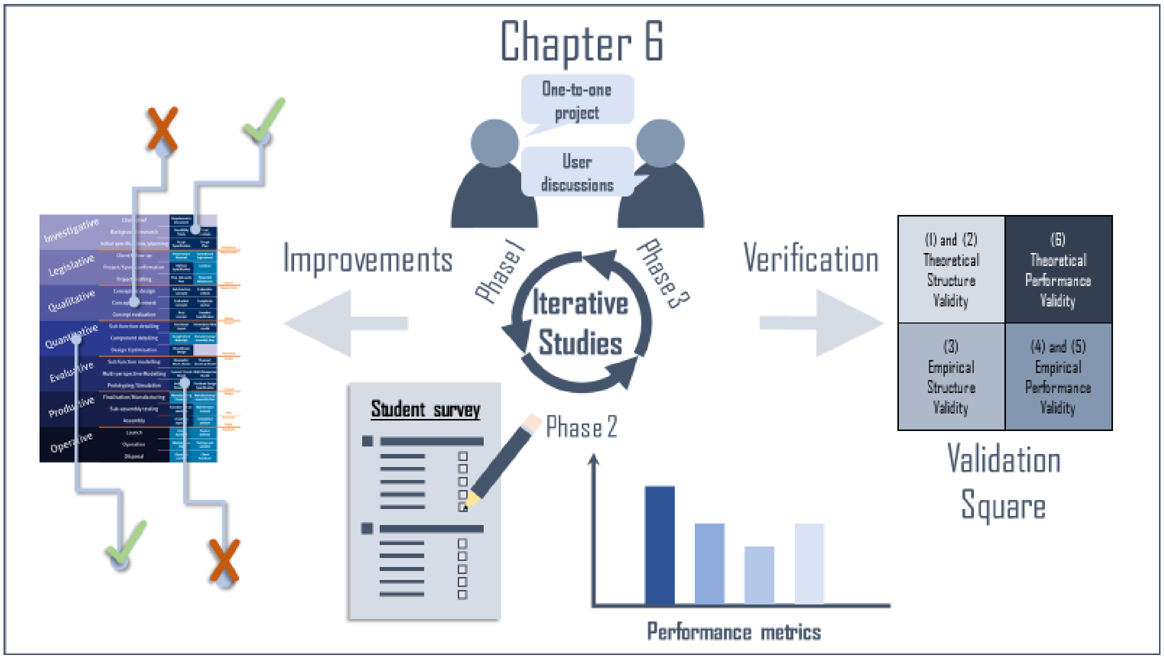


Figure 8-8 - Chapter 6 visual summary

Chapter 6 showed several studies done using the model, user survey and analysis of performance metrics. These were iterated over three phases and finalise the verification process by passing the thesis findings through the Validation Square.

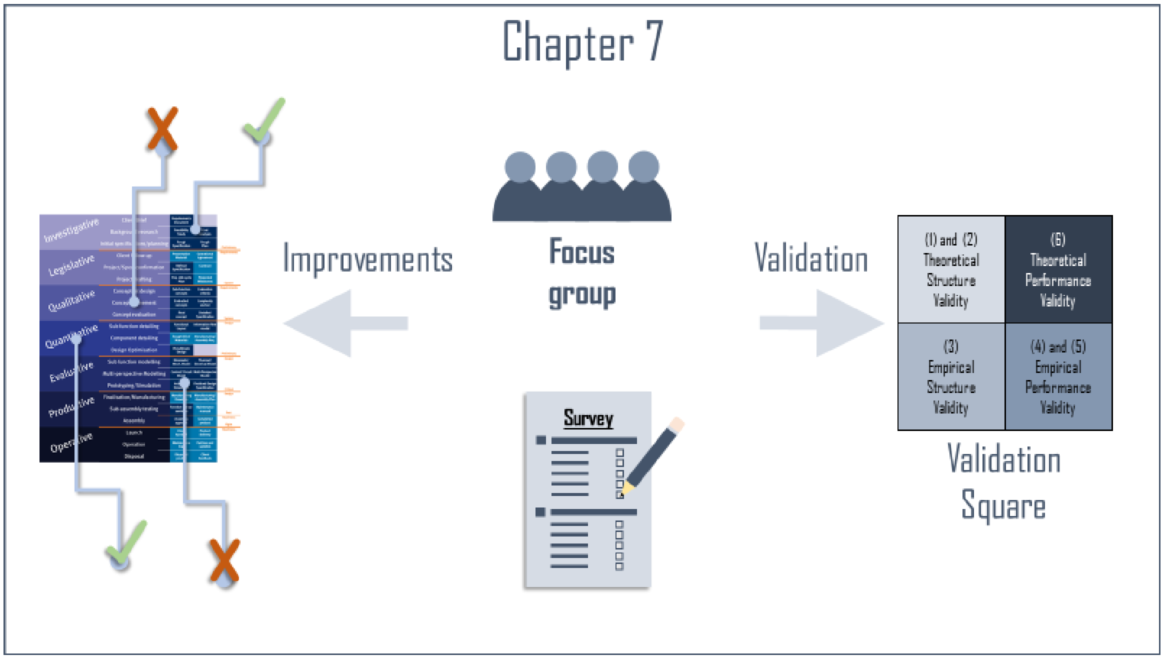


Figure 8-9 - Chapter 7 visual summary

Chapter 7 shows the final validation step of the Tiv-Model, where it is subjected to the critique and opinions of experts in the field of space systems engineering. The final changes are made to the model.

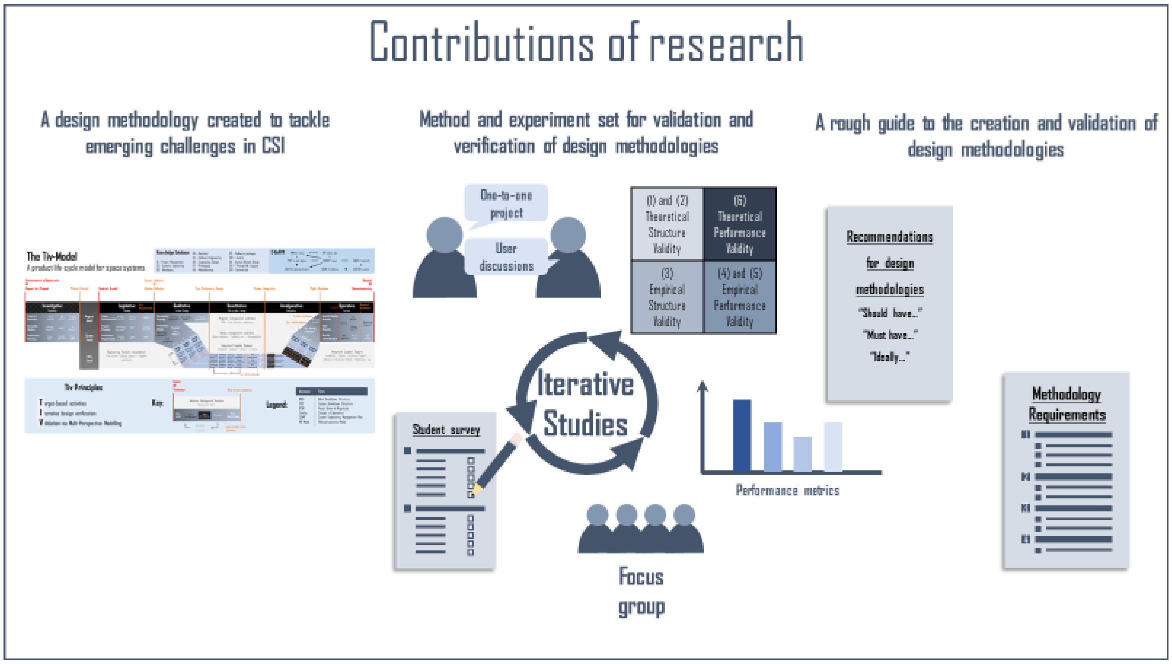


Figure 8-10 - Contributions of research visual summary

The contributions of this research included suggestions on the methodology design process, guidance on validation of said methodology and the Tiv-Model itself.

References

Adelson, B., & Freedle, R. (1988). Modelling software design within a problem-space architecture. In S. L. Newsome, W. R. Spillers, & S. Finger, *Design Theory '88* (pp. 56-80). London: Springer.

Adelson, B., & Soloway, E. (2007). A model of software design. *International Journal of Intelligent Systems*, 195-213.

Ahmed-Kristensen, S., & Wallace, K. M. (2004). Identifying and supporting the knowledge needs of novice designers within the aerospace industry. *Journal of Engineering Design*, 475-492.

Ahmed-Kristensen, S., & Wallace, K. M. (2004). Understanding the knowledge needs of novice designers in the aerospace industry. *Design Studies*, 155-173.

Ahmed-Kristensen, S., Wallace, K. M., & Langdon, P. (2001). *Identifying the strategic knowledge of experienced designers.* Cambridge: Engineering Design Centre, Cambridge University.

Ahmed-Kristensen, S., Wallace, K. M., Blessing, L., & Moss, M. (2000). Identifying differences between novice and experienced designers. *Engineering Design Conference 2000* (pp. 97-106). Uxbridge: Brunel University.

Alexander, K., & Clarkson, P. J. (2000). Good design practice for medical devices and equipment, Part I: A review of current literature. *Journal of Medical Engineering & Technology*, 5-13.

Alexander, K., & Clarkson, P. J. (2000). Good design practice for medical devices and equipment, Part II: design for validation. *Journal of Medical Engineering & Technology*, 53-62.

American Institute of Aeronautics and Astronautics. (2003). *AIAA Aerospace Design Engineers Guide.* Suffolk: Professional Engineering Publishing Ltd.

Andrews, D. J. (1986). An integrated approach to ship synthesis. *Transactions of the Royal Institution of Naval Architects*.

Andrews, D. J. (1998). A comprehensive methodology for the design of ships and other complex systems. *Proceedings of the Royal Society A*.

References

Armstrong, J. (2008). *Design Matters.* London: Springer.

Asimow, M. (1962). *Introduction to Design.* Englewood Cliffs: Prentice-Hall.

Badke-Schaub, P., Daalhuizen, J., & Roozenburg, N. (2011). Towards a Designer-Centred Methodology: Descriptive Considerations and Prescriptive Reflections. In H. Birkhofer, *The Future of Design Methodology* (pp. 181-197). London: Springer.

Baggen, R., Vaccaro, S., Llorens del Rio, D., & Padilla, J. (2011). Small-scale prototype of a Ku-band phased array for mobile satellite communications. *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications.* Torino: IEEE.

Bailey, R., Mistree, F., Allen, J., Emblemsvåg, J., & Pedersen, K. (2000). Validating Design Methods & Research: The Validation Square. *ASME Design Theory and Methodology Conference.* Baltimore, Maryland.

Bedingfield, K. L., Leach, R. D., & Alexander, M. B. (1996). *Spacecraft System Failures and Anomalies.* NASA.

Best, K. (2010). *The fundamentals of design management.* Ava Academia.

Binz, H., Keller, A., Kratzer, M., Messerle, M., & Roth, D. (2011). Increasing Effectiveness and Efficiency of Product Development - A Challenge for Design Methodologies and Knowledge Management. In H. Birkhofer, *The Future of Design Methodology* (pp. 79-90). London: Springer.

Birkhofer, H., Feldhusen, J., & Lindemann, U. (2009). Konstruktion 60. *Konstruktion 61*, 4-5.

Birkhofer, H., Jansch, J., & Kloberdanz, H. (2005). An Extensive and Detailed View of the Application of Design Methods and Methodology in Industry . *ICED 05: 15th International Conference on Engineering Design: Engineering Design and the Global Economy*, 1675-1686.

Birkhofer, H., Kloberdanz, H., Berger, B., & Sauer, T. (2002). Cleaning up Design Methods - Describing Methods Completely and Standardised. *Proceedings of DESIGN 2002* (pp. 17-22). Dubrovnik: DESIGN.

References

Birmingham, R. (1997). *Understanding engineering design: context, theory, and practice.* New York: Prentice Hall.

Bititci, U. S., & Nudurupati, S. (2002). Driving continuous improvement. *Manufacturing Engineering*, 230-235.

Blessing, L. T. (1994). A process-based approach to computer-supported engineering design. University of Twente, Enchede.

Blessing, L., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology.* London: Springer.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). *Product design for manufacture and assembly.* CRC Press.

Borg, J., Yan, X., & Juster, N. P. (2000). Exploring decisions' influence on life-cycle performance to aid "design for Multi-X". *Artificial intelligence for engineering design analysis and manufacturing*, 91-113.

Brien, P., & Rhodes, C. (2017). *The aerospace industry: statistics and policy.* House of Commons Library.

Brown, G., & Harris, W. (2018). *Types of satellites*. Retrieved from How stuff works: https://science.howstuffworks.com/satellite7.htm

BSI. (2013). *Design management systems. Guide to managing design in construction.* BSI Group.

Bundesrepublik Deutschland. (2004). V Modell XT Part 1: Fundamentals of the V Modell XT. Germany. Retrieved from https://www.scribd.com/document/269028202/V-Modell-XT-English

Chang, K. H. (2013). *Product Manufacturing and Cost Estimating using CAD/CAE.* Academic Press.

Christiaans, H. (1992). Creativity in design: The role of domain knowledge in designing. Lemma BV.

Clarkson, P. J., & Hamilton, J. R. (2000). 'Signposting', A parameter-driven task-based Model of the Design Process. *Research in Engineering Design*, 18-38.

References

Clausing, D. (1994). *Total Quality Development: a step-by-step guide to world class Concurrent Engineering.* ASME Press.

Cohen, L. (1995). *Quality function deployment : how to make QFD work for you.* Prentice-Hall.

Collier, C. A., & Glagola, C. R. (1998). *Engineering Economic and Cost Analysis.* Addison Wesley Longman.

Cova Scientific. (2016, Feb 17). *Polymer Outgassing & NASA Outgassing Standards*. Retrieved from Cova Scientific: https://www.covascientific.com/blog/outgassing

Cross, N. (2000). *Engineering Design Methods: Strategies for Product Design.* Wiley.

Cucinotta, F. A., & Durante, M. (2006). Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *The Lancet Oncology*, 431-435.

Dale, B. G., & Shaw, P. (1989). *Failure mode and effects analysis: a study of its use in the motor industry.* Manchester School of Management.

Demoly, F., Dutarte, O., Yan, X. T., Eynard, B., & Ki. (2013). Product relationships management enabler for concurrent engineering and product lifecycle management. *Computers in Industry*, 833-848.

Dent, R. J., & Storey, D. A. (2004). *Benchmarking the performance of design activities in construction : a summary report and key performance indicators.* London: CIRIA.

Der Beauftragte der Bundesregierung für Informationstechnik. (2018). *V Modell XT*. Retrieved from Der Beauftragte der Bundesregierung für Informationstechnik: https://www.cio.bund.de/Web/DE/Architekturen-und-Standards/V-Modell-XT/vmodell_xt_node.html

Dunar, A. J., & Waring, S. P. (2012). *Power to Explore: A History of Marshal Space Flight Centre 1960-1990.* CreateSpace.

Earl, C., Johnson, J., & Eckert, C. (2005). Complexity. In J. Clarkson, & C. Eckert, *Design Process Improvement* (pp. 174-197). London: Springer.

References

Easterbrook, S. (2010, Nov 29). *The difference between Verification and Validation*. Retrieved from Serendipity: http://www.easterbrook.ca/steve/2010/11/the-difference-between-verification-and-validation/

Economic Development Committee for the Mechanical Engineering Industry. (1971). *Market research in action: a guide for company management.* London: H.M.S.O.

Ehrlenspiel, K. (2003). *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit.* Munich: Hanser.

Ellery, A. (2000). *An Introduction to Space Robotics.* London: Springer.

Elsmore, P. (2001). *Organisational Culture: Organisational Change?* Gower.

FDA. (1997). *Design control guidance for medical device manufacturers.*

Finger, S., & Dixon, J. (1989). A review of research in mechanical engineering design. Part I: Descriptive, prescriptive, and computer-based models of design processes. *Research in Engineering Design*, 51-67.

Firesmith, D. (2013, Nov 11). *Using V Models for testing*. Retrieved from SEI Insights: https://insights.sei.cmu.edu/sei_blog/2013/11/using-v-models-for-testing.html

Fortescue, P., Swinerd, G., & Stark, J. (2011). *Spacecraft Systems Engineering.* Wiley.

French, M. J. (1985). *Conceptual Design for Engineers.* Berlin: Springer.

Frey, D. D., & Dym, C. L. (2006). Validation of design methods: lessons from medicine. *Research in Engineering Design*, 45-57.

Frost, R. B. (1992). A converging model of the design process: analysis and creativity, the ingredients of synthesis. *Journal of Engineering Design*, 117-126.

Gero, J. S., Tversky, B. D., & Gobert, J. (1999). Expertise in the comprehension of architectural plans: Contribution of representation and domain knowledge. *Visual And Spatial Reasoning In Design '99.* Sydney: University of Sydney.

References

Göker, M. H. (1997). The effects of experience during design problem solving. *Design Studies*, 405-426.

Grady, J. O. (2000). *System Requirements Analysis.* McGraw-Hill.

Griffiths, B. (2002). *Engineering Drawing for Manufacture.* Butterworth-Heinemann.

Hall, A. (2011). Experimental Design: Design Experimentation. *Design Issues*, 17-26.

Hall, A. D. (1962). *A Methodology for Systems Engineering.* Van Nostrand.

Hammar, M. (2018). *ISO9001 Design Verification vs Design Validation*. Retrieved from Advisera: https://advisera.com/9001academy/knowledgebase/iso9001-design-verification-vs-design-validation/

Hansen, R. H., Pascale, J. V., De Benedictis, T., & Rentzepis, P. M. (1965). Effect of atomic oxygen on polymers. *Journal of Polymer Science*.

Harkness, P., McRobb, M., Lutzkendorf, P., Milligan, R., Feeney, A., & Clark, C. (2014). Development status of AEOLDOS – A deorbit module for small satellites. *Advances in Space Research*, 82-91.

Herrick, C. N. (1968). *Electronic circuits.* Columbus: Merrill.

Herrick, C. N. (1969). *Introduction to Electronic Communication.* Merril.

Hibbeler, R. C., & Fan, S. C. (1997). *Engineering mechanics: dynamics.* London: Prentice-Hall.

Hill, P. H. (1970). *The science of engineering design.* New York: Holt, Rinehart and Winston.

Hong, Y. C., & Choi, I. (2011). Three dimensions of reflective thinking in solving design problems: A conceptual model. *Educational Technology Research and Develoment*, 687-710.

Hooi. Tan, L. (1986). Industrial robot simulation. Glasgow: University of Strathclyde.

Houghton, A. B. (1995). *Mechanical Analysis and Design.* Prentice-Hall.

Huber, L. (2010). Validation of Analytical Methods. Retrieved from https://www.chemass.si/validation-of-analytical-methods-primer

References

Hubka, V., & Eder, W. E. (1999). Theory of Technical Systems in the curriculum of Engineering Schools. *Proceedings of the International Conference on Engineering Design, ICED 99.* Munich: F.R. Germany.

Hubka, V., & Eder, W. E. (2002). Theory of technical systems and engineering design synthesis. In A. Chakrabarti, *Engineering Design Synthesis* (pp. 49-66). London: Springer.

Hunt, E. C., & Butman, B. S. (1995). *Marine engineering economics and cost analysis.* Centreville: Cornell Maritime Press.

IASB. (2018, Mar 12). *Spacecraft Charging*. Retrieved from SPENVIS: https://www.spenvis.oma.be/help/background/charging/charging.html

ISO/IEC/IEEE. (2015). Systems and software engineering — System life cycle processes. ISO.

Jacques, R. P. (1981). Design: Science: Method. *Design Research Society.* Guildford: Westbury House.

Jaynes, E. T. (1957). Information Theory and Statistical Mathematics. *The Physical Review*, 620-630.

Jerrard, R., Hands, D., & Ingram, J. (2002). *Design management case studies.* London: Routledge.

Johnson, M. R. (1994). *The Galileo High Gain Antenna Deployment Anomaly.* NASA.

Jonassen, D. H. (2011). *Learning to Solve Problems: A Handbook for Designing Problem-Solving Learning Environments.* New York: Routledge.

Juster, N. (1985). *The design process and design methodologies.* University of Leeds.

Kazakci, A. O., Gillier, T., Piat, G., & Hatchuel, A. (2014). Brainstorming versus creative design reasoning. *IDEAS Working Paper Series from RePec*.

Keller, A., & Binz, H. (2009). Requirements on Engineering Design Methodologies. *ICED'09* (pp. 203-214). Palo Alto: ICED.

Kendall, K. E., & Kendall, J. E. (2008). *Systems analysis and design.* Upper Saddle River: Pearson/Prentice-Hall.

References

Koenig, D. T. (2007). *Manufacturing engineering principles for optimisation.* ASME Press.

Lawson, B. R. (2006). *How Designers Think – The Design Process Demystified.* Cambridge: University Press.

Leete, R. J. (2002). *Design for on-orbit spacecraft servicing.* NASA.

Lester, A. (2013). *Project management, planning and control: managing engineering construction and manufacturing projects to PMI, APM and BSI standards.* Butterworth-Heinemann .

Li, B., & Zhang, H. M. (2013). Application of Data Flow Diagram on Simulation Software Test Case Generation. *Advanced Materials Research*, 791-793.

Long, D., & Scott, Z. (2011). *A Primer for Model-Based Systems Engineering.* Vitech Corporation.

Macdonald, R. (2014). Feasibility study into a novel vessel design for accessing offshore wind turbines. University of Strathclyde.

Mallik, A. K., Ghosh, A., & Dittrich, G. (1994). *Kinematic analysis and synthesis of mechanisms.* CRC Press.

Mandel, P., & Chryssostomidis, C. (1972). A Design Methodology for Ships and Other Complex System. *Phil. Trans. R. Soc. A*, 85-98.

Manjula, B., Waldron, M. B., Jelinek, W., Ownes, D., & Waldron, K. J. (1987). A Study of VisuaI Recall Differences between Expert and Naive Mechanical Designers. *International Congress on Planning and Design Theory* (pp. 86-93). Boston: The American Society of Mechanical Engineers.

Maritan, D. (2015). *Practical Manual of Quality Function Deployment.* London: Springer.

Means, J. A., & Adams, T. (2005). *Facilitating the Project Lifecycle: The Skills & Tools to Accelerate Progress for Project Managers, Facilitators, and Six Sigma Project Teams.* Jossy-Bass.

Melville, C., & Yan, X. T. (2015). Universal connection interface for modular and swarm space robotics. *IET, IMechE, SSI and SMeSTech Space Robotics Symposium.* Glasgow.

References

Melville, C., & Yan, X. T. (2016). Tiv-Model - An attempt at breaching the industry adoption barrier for new complex system design methodologies. In P. Hehenberger, & D. Bradley, *Mechatronic Futures* (pp. 41-57). London: Springer.

Miller, R., Hobday, M., Leroux-Demers, T., & Olleros, X. (1995). Innovation in Complex Systems Industries: The Case of Flight Simulation. *Industrial and Corporate Change*.

Misra, S. C. (2015). *Design Principles of Ships and Marine Structures.* CRC Press.

MOD. (2017). *UK Defence in Numbers.* Retrieved from gov.uk: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652915/UK_Defence_in_Numbers_2017_-_Update_17_Oct.pdf

Molloy, O., Warman, E. A., & Tilley, S. (1998). *Design for manufacturing and assembly: concepts, architectures and implementation.* Springer.

Mosher, T. (1999). Conceptual Spacecraft Design Using a Genetic Algorithm Trade Selection Process. *Journal of Aircraft*.

NASA. (2010, Apr 26). *Micrometeoroids and Orbital Debris (MMOD)* . Retrieved from NASA: https://www.nasa.gov/centers/wstf/laboratories/hypervelocity/mmod.html

NASA. (2020). *NASA Systems Engineering Handbook.* NASA.

Neudeck, P. G., Prokop, N. F., Greer, L. C., Chen, L. Y., & Krasowski, M. J. (2010). Low Earth Orbit Space Environment Testing of Extreme Temperature 6H-SiC JFETs on the International Space Station. *Materials Science Forum*, 579-582.

NOAA. (2018). *Extreme Events*. Retrieved from National Centers for Environmental Information: https://www.ncdc.noaa.gov/climate-information/extreme-events

Odam, K. D. (1976). Computer aided circuit modelling. University of Strathclyde.

O'Donovan, B., Eckert, C., Clarkson, J., & Browning, T. (2005). Design planning and modelling. In J. Clarkson, & C. Eckert, *Design Process Improvement* (pp. 60-87). London: Springer.

References

Ogilvie, A., Allport, J., Hannah, M., & Lymer, J. (2008). Autonomous robotic operations for on-orbit satellite servicing. *Proc. SPIE 6958, Sensors and Systems for Space Applications II.* SPIE.

Pahl, G., & Beitz, W. (1996). *Engineering Design.* Design Council.

Pidaparti, R. M. (2017). *Engineering Finite Element Analysis.* San Rafael: Morgan & Claypool.

Pippin, H. G., & Bourrasa, R. J. (1995). *Effects of space exposure on metals flown on the Long Duration Exposure Facility.*

Pugh, S. (1988). Total Design: towards a theory of total design. Glasgow: University of Strathclyde.

Pugh, S. (1990). *Total Design: Integrated Methods for sucessful Product Engineering.* Prentice Hall.

Queen Elizabeth Cruises. (2018). *HMS Queen Elizabeth aircraft carrier*. Retrieved from Queen Elizabeth Cruises: http://www.queenelizabethcruises.net/hms-queen-elizabeth-aircraft-carrier/

Quirk, T. J. (2014). *Excel 2010 for Engineering Statistics.* Cham: Springer.

Renev, I. A., & Cheehurin, L. S. (2016). Application of TRIZ in building industry: study of current situation. *Prodedia CIRP*, 209-215.

Richards, M. G. (2007). On-orbit serviceability of space system architectures.

Roth, D., Binz, H., & Watty, R. (2010). Generic Structure of Knowledge within the Product Development Process. *Proceedings of DESIGN 2010*, (pp. 1681-1690). Dubrovnik.

Rowell, W., Duffy, A. H., Boyle, I. M., & Masson, N. (2009). The nature of eingineering change in a complex product development cycle. *Systems Engineering Research.*

Schmidt-Kretschmer, M., & Blessing, L. (2006). Strategic aspects of design methodologies: Understood or underrated? *Proceedings of DESIGN 2006*, (pp. 125-130). Dubrovnik.

Seepersad, C., Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J., & Mistree, F. (2006). The Validation Square: How does one Verify and Validate a Design Method? In K. Lewis, W. Chen, & L. Schmidt, *Decision Making in Engineering Design.* ASME Press.

References

Shigley, J. E. (1969). *Kinematic analysis of mechanisms.* McGraw-Hill.

Smith, W. G. (1943). *Engineering Kinematics.* New York: McGraw-Hill.

Snell, M. (1997). *Cost-benefit analysis for engineers and planners.* London: T. Telford.

Spillers, W. R. (1975). *Iterative structural design.* North-holland.

Stark, J. (2015). *Product Lifecycle Management (Volume 1) : 21st Century Paradigm for Product Realisation.* Cham: Springer.

Straub, J. (2014). Extending the orbital services model beyond computing, communications and sensing. *IEEE Aerospace Conference.* Big Sky: IEEE.

Stuart, J. S. (2002). A multiple viewpoint modular design methodology. Glasgow: University of Strathclyde.

Suh, N. P. (1999). A Theory of Complexity, Periodicity and the Design Axioms. *Research in Engineering Design*, 116-132.

Tafazoli, M. (2009). A study of on-orbit spacecraft failures. *Acta Astronautica*, 195-205.

Taghizadegan, S. (2006). *Essentials of Lean Six Sigma.* Butterworth-Heinemann .

Tate, D., & Norlund, M. (2001). Research methods for design theory. *Proceedings of the ASME Design Engineering Technical Conference*, 115-124.

The Rover Team. (2006). The ExoMars rover and Pasteur payloadPhase A study: an approach toexperimental astrobiology. *International Journal of Astrobiology*, 221-241.

Thierauf, R. J. (1986). *Systems analysis and design: a case study approach.* Merrill Pub. Co.

Visser, W. (2009). Design: one, but in different forms. *Design Studies*, 187-223.

Watts, F. B. (2011). *Engineering Documentation Control Handbook.* Elsevier.

Wilson, P., & Mantooth, H. A. (2013). *Model-Based Engineering for Complex Electronic Systems.* Newnes.

References

Wodehouse, A., & Ion, W. (2012). Augmenting the 6-3-5 method with design information. *Research in Engineering Design*, 5-15.

Workman, D. (2017, May 21). *Aerospace Exports by Country*. Retrieved from WTEx: http://www.worldstopexports.com/aerospace-exports-by-country/

Wynn, D., & Clarkson, J. (2005). Models of designing. In J. Clarkson, & C. Eckert, *Design Process Improvement* (pp. 34-59). London: Springer.

Xu, W., Liang, B., Li, B., & Xu, Y. (2011). A universal on-orbit servicing system used in the geostationary orbit. *Advances in Space Research*, 95-119.

Yan, X. (2003). A multiple perspective product modelling and simulation approach to enhancing engineering design decision making. *Concurrent Engineering*, 221-234.

Yan, X. T., & Sharpe, J. J. (1994). A system simulation platform for mechatronic product design. *European Simulation Multi-Conference*, (pp. 789-793).

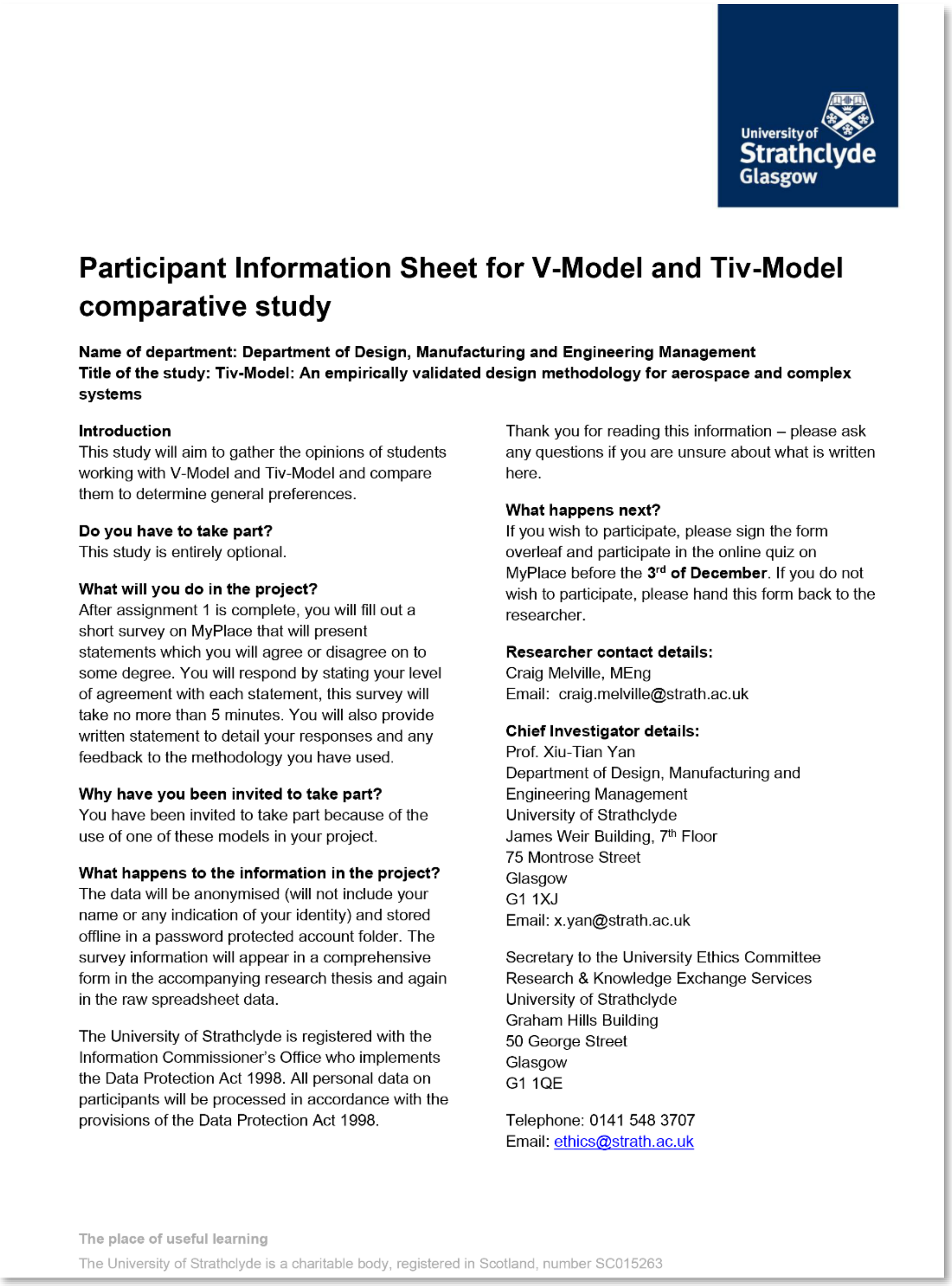
Yan, X. T., Brinkmann, W., Palazzetti, R., Melville, C., Li, Y. L., Bartsch, S., & Kirchner, F. (2018). Integrated Mechanical, Thermal, Data, and Power Transfer Interfaces for Future Space Robotics. *Frontiers in Robotics and AI*.

Yan, X.-T., & Zante, R. (2010). A Mechatronic Design process and its application. In D. Bradley, & D. W. Russel, *Mechatronics in Action* (pp. 55-70). Springer.

Zipfel, P. H. (2014). *Modelling and simulation of aerospace vehicle dynamics.* AIAA.

Appendix A - Comparative study

A.i Comparative study Participant Information and consent form



University of Strathclyde Glasgow

Participant Information Sheet for V-Model and Tiv-Model comparative study

Name of department: Department of Design, Manufacturing and Engineering Management
Title of the study: Tiv-Model: An empirically validated design methodology for aerospace and complex systems

Introduction
This study will aim to gather the opinions of students working with V-Model and Tiv-Model and compare them to determine general preferences.

Do you have to take part?
This study is entirely optional.

What will you do in the project?
After assignment 1 is complete, you will fill out a short survey on MyPlace that will present statements which you will agree or disagree on to some degree. You will respond by stating your level of agreement with each statement, this survey will take no more than 5 minutes. You will also provide written statement to detail your responses and any feedback to the methodology you have used.

Why have you been invited to take part?
You have been invited to take part because of the use of one of these models in your project.

What happens to the information in the project?
The data will be anonymised (will not include your name or any indication of your identity) and stored offline in a password protected account folder. The survey information will appear in a comprehensive form in the accompanying research thesis and again in the raw spreadsheet data.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?
If you wish to participate, please sign the form overleaf and participate in the online quiz on MyPlace before the **3rd of December**. If you do not wish to participate, please hand this form back to the researcher.

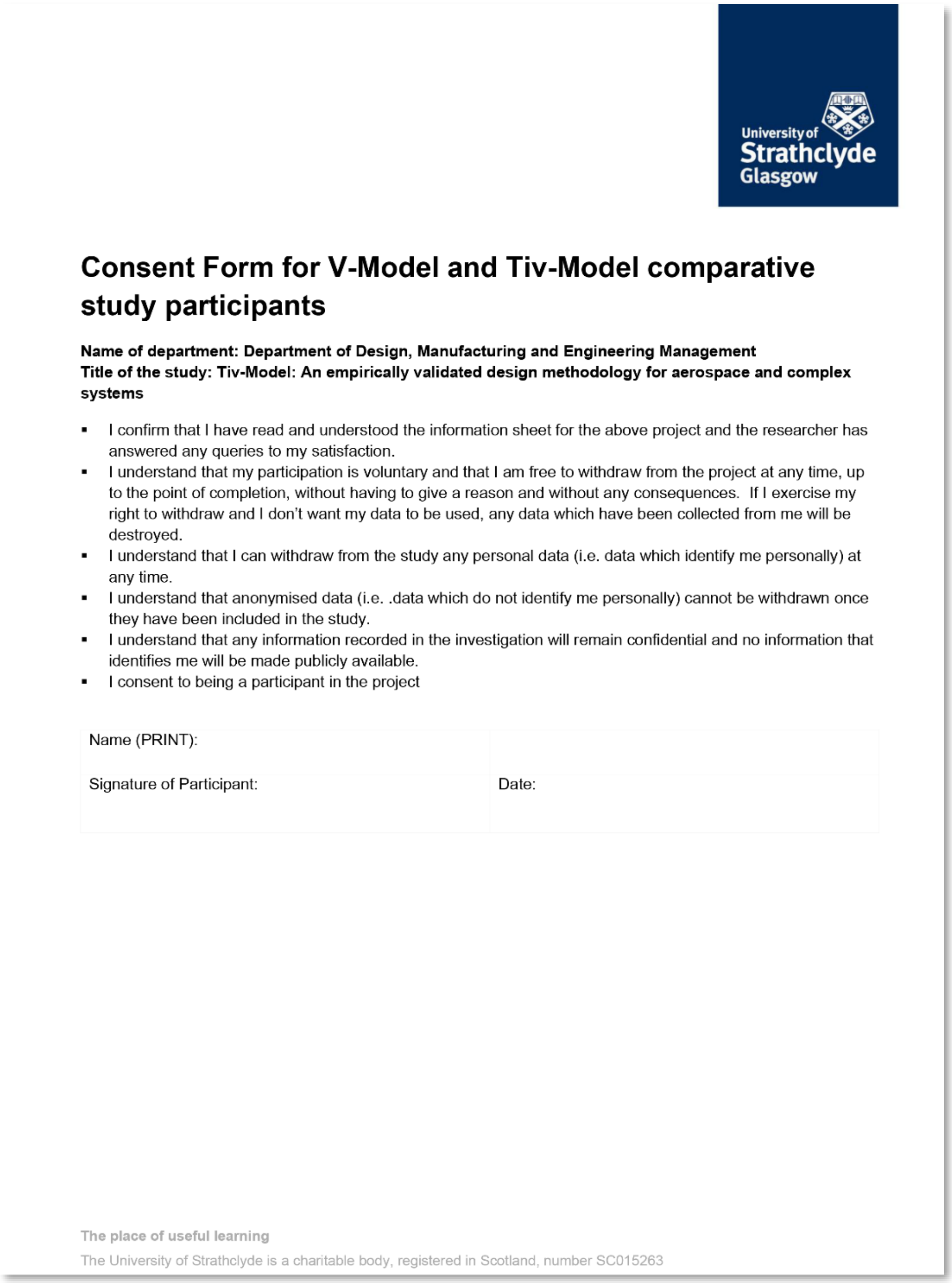
Researcher contact details:
Craig Melville, MEng
Email: craig.melville@strath.ac.uk

Chief Investigator details:
Prof. Xiu-Tian Yan
Department of Design, Manufacturing and Engineering Management
University of Strathclyde
James Weir Building, 7th Floor
75 Montrose Street
Glasgow
G1 1XJ
Email: x.yan@strath.ac.uk

Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE

Telephone: 0141 548 3707
Email: ethics@strath.ac.uk

The place of useful learning
The University of Strathclyde is a charitable body, registered in Scotland, number SC015263



University of Strathclyde Glasgow

Consent Form for V-Model and Tiv-Model comparative study participants

Name of department: Department of Design, Manufacturing and Engineering Management
Title of the study: Tiv-Model: An empirically validated design methodology for aerospace and complex systems

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences. If I exercise my right to withdraw and I don't want my data to be used, any data which have been collected from me will be destroyed.
- I understand that I can withdraw from the study any personal data (i.e. data which identify me personally) at any time.
- I understand that anonymised data (i.e. .data which do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project

Name (PRINT):	
Signature of Participant:	Date:

The place of useful learning
The University of Strathclyde is a charitable body, registered in Scotland, number SC015263

A.ii Comparative study quiz questions

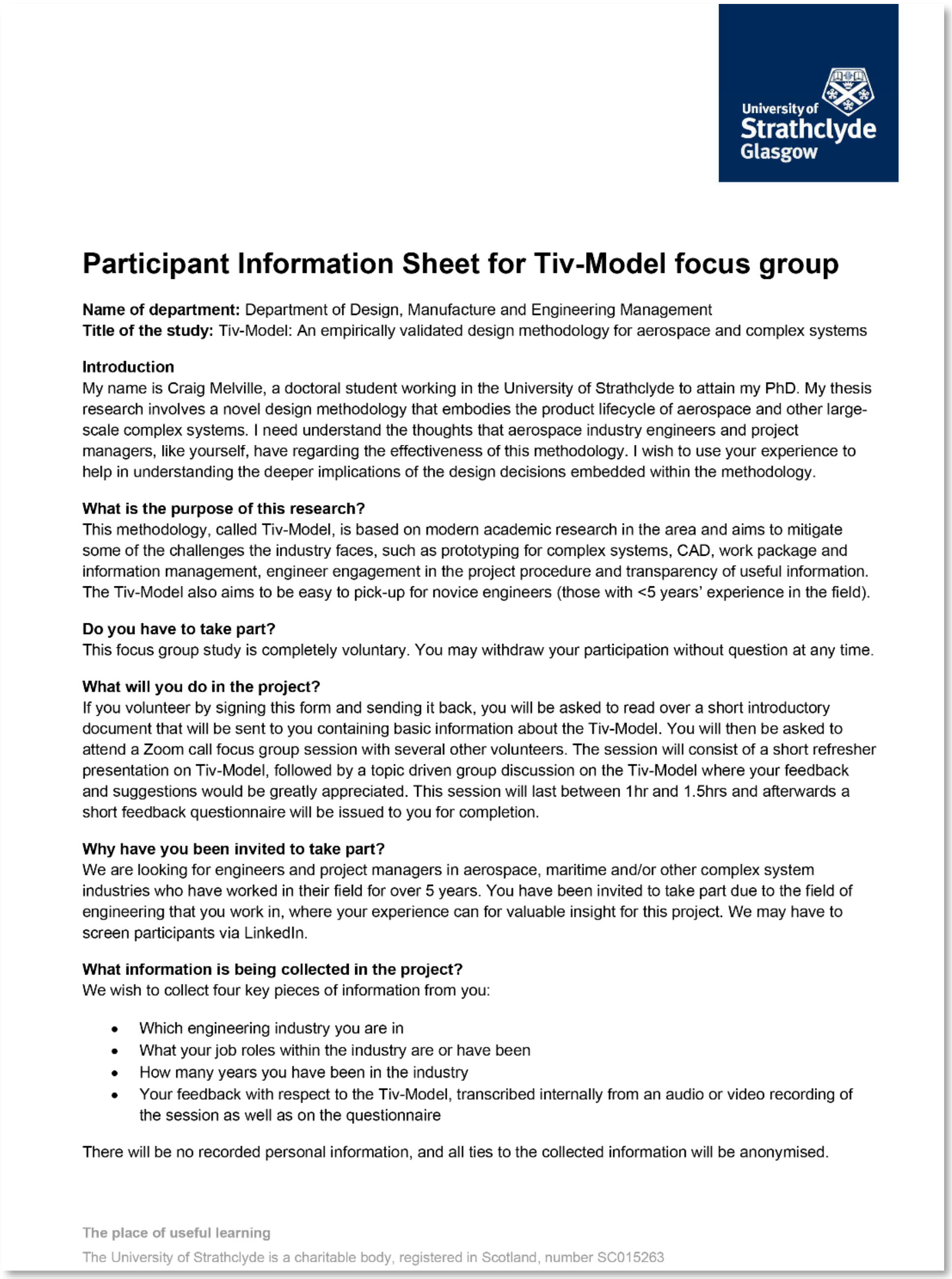
1. Overall, I found the methodology difficult to use
2. I would definitely NOT use this model to develop mechatronic systems
3. I would use this model instead of Pugh's TDM if I have to develop a mechatronic system
4. I found the rules of the model clear and easy to understand
5. I found that the model was suitable for this kind of project
6. I found that my existing knowledge worked well with the model
7. I found that I was limited to specific means or methods in order to achieve my goal
8. I believe that the model would reduce the effort required to produce mechatronic systems
9. Overall, I think this model does NOT provide an effective solution to the development of mechatronic systems
10. I am NOT confident about applying this method in practice
11. I found it difficult to apply the model to the project
12. Using this model would make it more difficult to complete mechatronic projects
13. This model would make it easier for designers to produce mechatronic systems
14. Using this model would make it easier to communicate concepts in a mechatronic project
15. I found the model easy to learn
16. Overall, the model's information was well presented
17. I would use this model again in a general product development project
18. I found the model complex and difficult to follow
19. Overall, I found the model to be useful
20. Overall, I found that the model freely allowed me to make design decisions
21. The Macro-level model was useful for this project
22. The Micro-level problem solving technique was useful for this project
23. The Mid-level task management was useful for this project

A.iii Comparative study quiz answers

1. Strongly agree
2. Agree
3. Not sure
4. Disagree
5. Strongly disagree

Appendix B - Focus group study

B.i Focus group study Participant Information and consent form



University of
Strathclyde
Glasgow

Participant Information Sheet for Tiv-Model focus group

Name of department: Department of Design, Manufacture and Engineering Management
Title of the study: Tiv-Model: An empirically validated design methodology for aerospace and complex systems

Introduction
My name is Craig Melville, a doctoral student working in the University of Strathclyde to attain my PhD. My thesis research involves a novel design methodology that embodies the product lifecycle of aerospace and other large-scale complex systems. I need understand the thoughts that aerospace industry engineers and project managers, like yourself, have regarding the effectiveness of this methodology. I wish to use your experience to help in understanding the deeper implications of the design decisions embedded within the methodology.

What is the purpose of this research?
This methodology, called Tiv-Model, is based on modern academic research in the area and aims to mitigate some of the challenges the industry faces, such as prototyping for complex systems, CAD, work package and information management, engineer engagement in the project procedure and transparency of useful information. The Tiv-Model also aims to be easy to pick-up for novice engineers (those with <5 years' experience in the field).

Do you have to take part?
This focus group study is completely voluntary. You may withdraw your participation without question at any time.

What will you do in the project?
If you volunteer by signing this form and sending it back, you will be asked to read over a short introductory document that will be sent to you containing basic information about the Tiv-Model. You will then be asked to attend a Zoom call focus group session with several other volunteers. The session will consist of a short refresher presentation on Tiv-Model, followed by a topic driven group discussion on the Tiv-Model where your feedback and suggestions would be greatly appreciated. This session will last between 1hr and 1.5hrs and afterwards a short feedback questionnaire will be issued to you for completion.

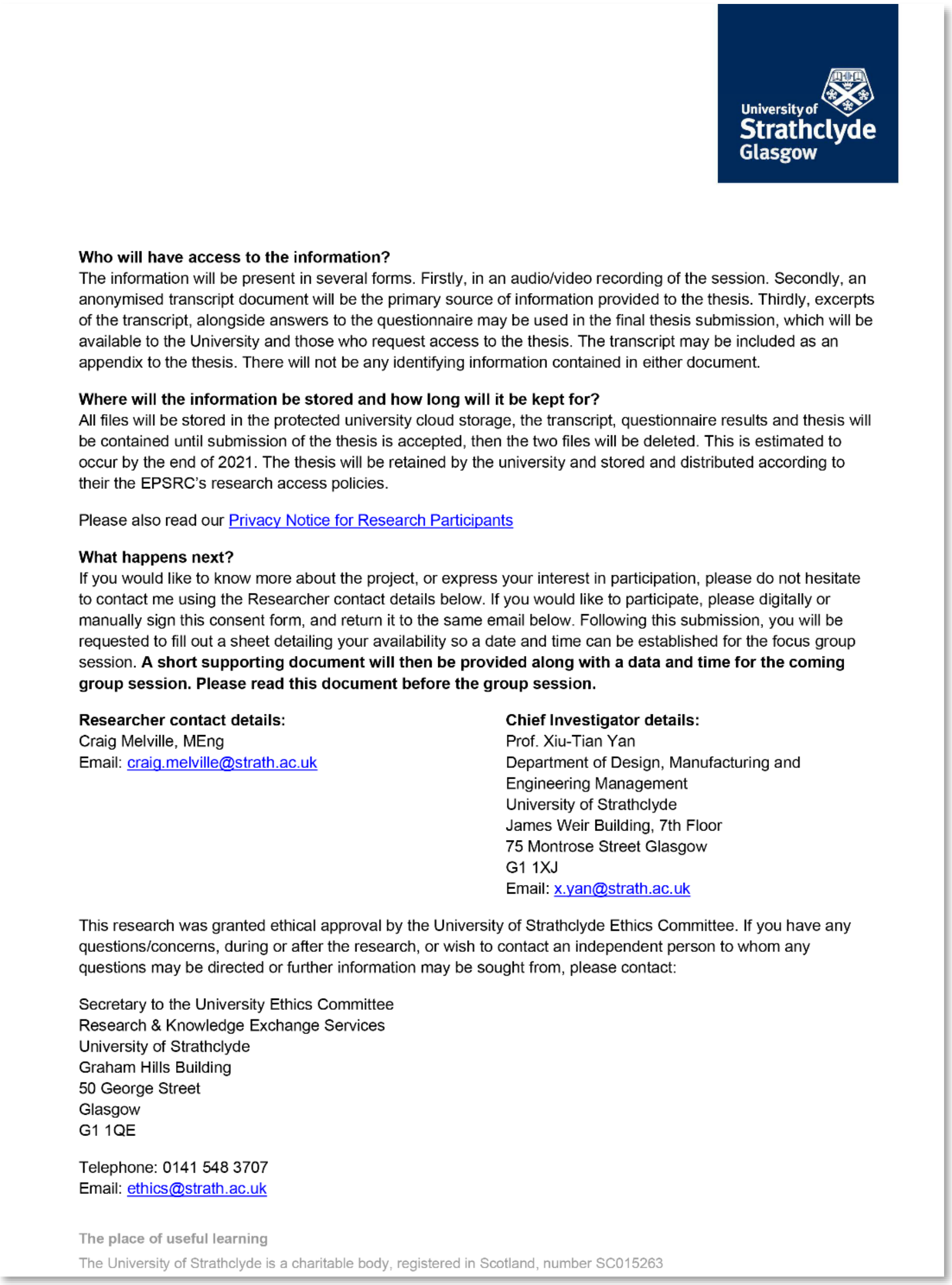
Why have you been invited to take part?
We are looking for engineers and project managers in aerospace, maritime and/or other complex system industries who have worked in their field for over 5 years. You have been invited to take part due to the field of engineering that you work in, where your experience can for valuable insight for this project. We may have to screen participants via LinkedIn.

What information is being collected in the project?
We wish to collect four key pieces of information from you:

- Which engineering industry you are in
- What your job roles within the industry are or have been
- How many years you have been in the industry
- Your feedback with respect to the Tiv-Model, transcribed internally from an audio or video recording of the session as well as on the questionnaire

There will be no recorded personal information, and all ties to the collected information will be anonymised.

The place of useful learning
The University of Strathclyde is a charitable body, registered in Scotland, number SC015263



Who will have access to the information?
The information will be present in several forms. Firstly, in an audio/video recording of the session. Secondly, an anonymised transcript document will be the primary source of information provided to the thesis. Thirdly, excerpts of the transcript, alongside answers to the questionnaire may be used in the final thesis submission, which will be available to the University and those who request access to the thesis. The transcript may be included as an appendix to the thesis. There will not be any identifying information contained in either document.

Where will the information be stored and how long will it be kept for?
All files will be stored in the protected university cloud storage, the transcript, questionnaire results and thesis will be contained until submission of the thesis is accepted, then the two files will be deleted. This is estimated to occur by the end of 2021. The thesis will be retained by the university and stored and distributed according to their the EPSRC's research access policies.

Please also read our Privacy Notice for Research Participants

What happens next?
If you would like to know more about the project, or express your interest in participation, please do not hesitate to contact me using the Researcher contact details below. If you would like to participate, please digitally or manually sign this consent form, and return it to the same email below. Following this submission, you will be requested to fill out a sheet detailing your availability so a date and time can be established for the focus group session. **A short supporting document will then be provided along with a data and time for the coming group session. Please read this document before the group session.**

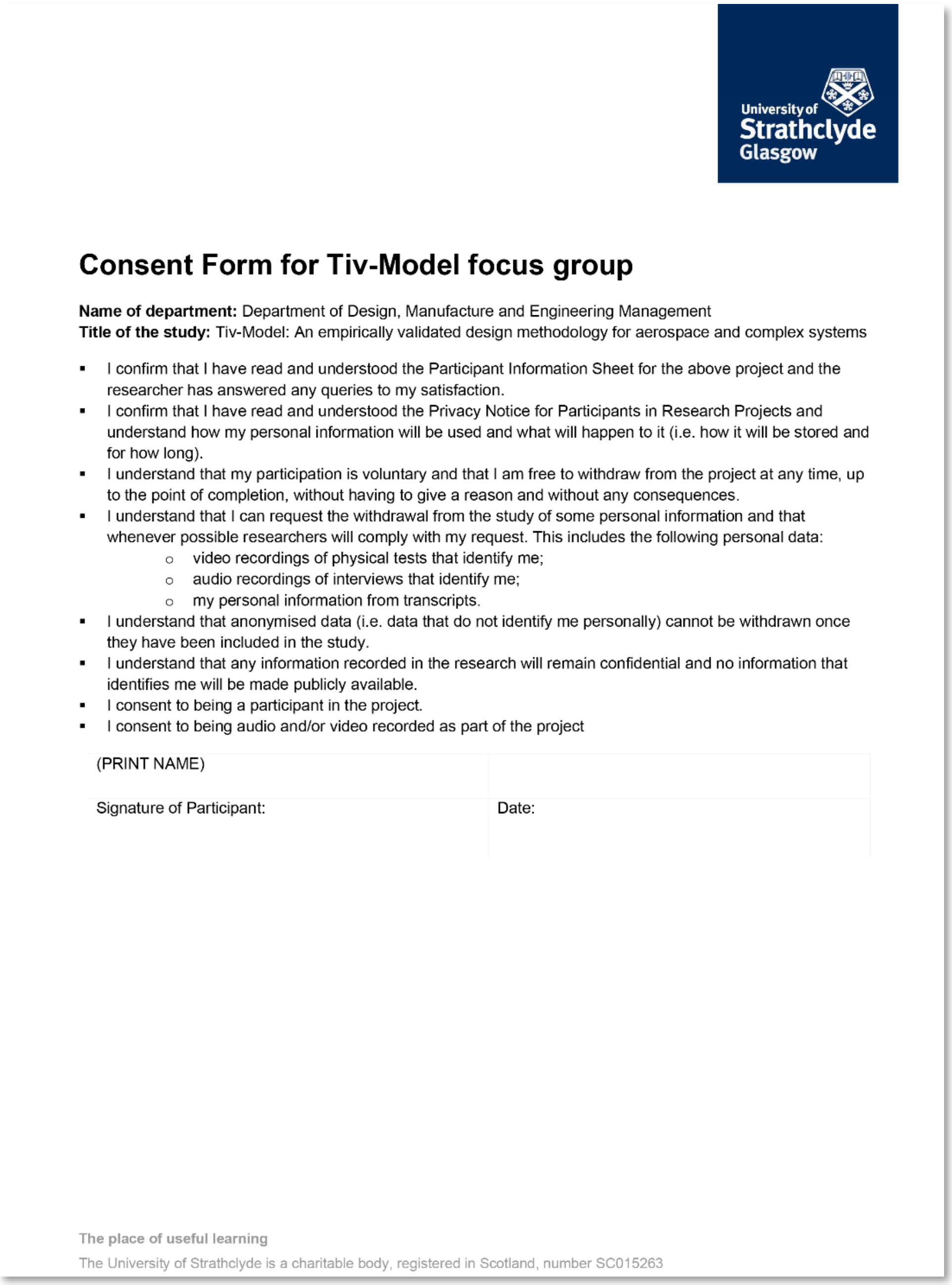
Researcher contact details:
Craig Melville, MEng
Email: craig.melville@strath.ac.uk

Chief Investigator details:
Prof. Xiu-Tian Yan
Department of Design, Manufacturing and
Engineering Management
University of Strathclyde
James Weir Building, 7th Floor
75 Montrose Street Glasgow
G1 1XJ
Email: x.yan@strath.ac.uk

This research was granted ethical approval by the University of Strathclyde Ethics Committee. If you have any questions/concerns, during or after the research, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE

Telephone: 0141 548 3707
Email: ethics@strath.ac.uk



University of Strathclyde Glasgow

Consent Form for Tiv-Model focus group

Name of department: Department of Design, Manufacture and Engineering Management
Title of the study: Tiv-Model: An empirically validated design methodology for aerospace and complex systems

- I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction.
- I confirm that I have read and understood the Privacy Notice for Participants in Research Projects and understand how my personal information will be used and what will happen to it (i.e. how it will be stored and for how long).
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences.
- I understand that I can request the withdrawal from the study of some personal information and that whenever possible researchers will comply with my request. This includes the following personal data:
    - video recordings of physical tests that identify me;
    - audio recordings of interviews that identify me;
    - my personal information from transcripts.
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project.
- I consent to being audio and/or video recorded as part of the project

(PRINT NAME)	
Signature of Participant:	Date:

The place of useful learning

The University of Strathclyde is a charitable body, registered in Scotland, number SC015263

B.ii Focus group study presentation material

Focus group presentation

26/02/21

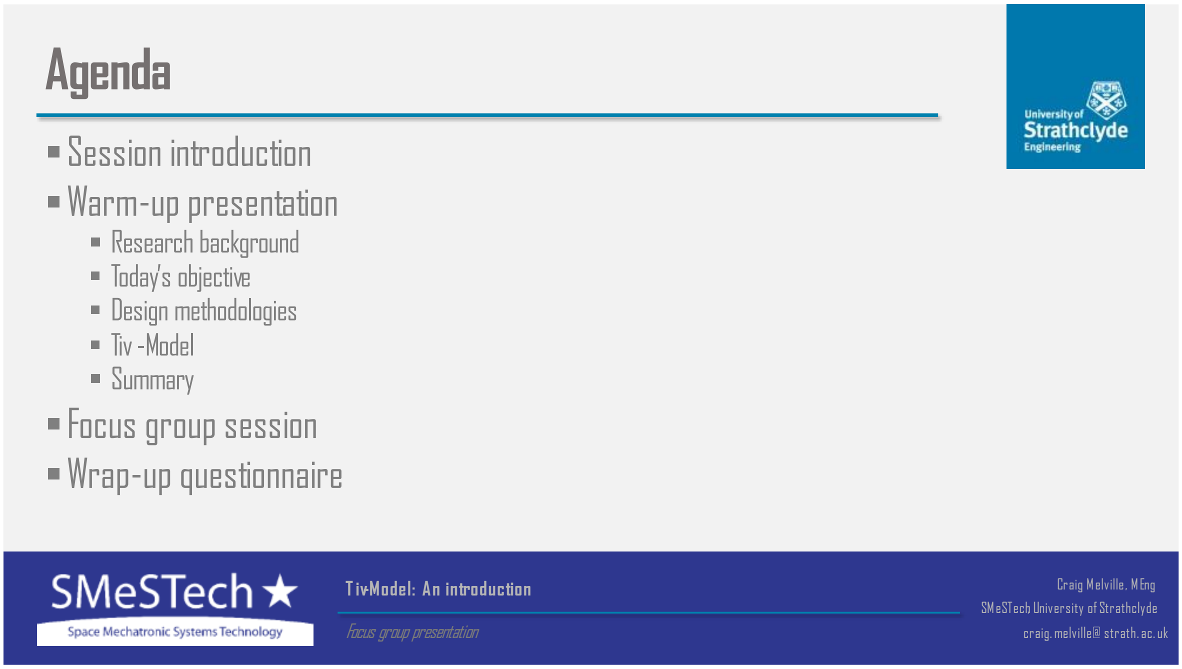
Tiv-Model: An introduction

Craig Melville

Craig Melville, MEng
SMeSTech , University of Strathclyde
craig.melville@strath.ac.uk
07702016312

SMeSTech★
Space Mechatronic Systems Technology

University of Strathclyde Engineering



Agenda

- Session introduction
- Warm-up presentation
  - Research background
  - Today's objective
  - Design methodologies
  - Tiv -Model
  - Summary
- Focus group session
- Wrap-up questionnaire

University of Strathclyde Engineering

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction
Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@ strath.ac.uk

Research background

- Craig Melville
- MEng in Product Design Engineering from University of Strathclyde
- Systems Engineer at Ultra Maritime
- Writing PhD in Aerospace Engineering Design Theory through Space Mechatronic Systems Technology lab
- Lab focuses on robotics and space design engineering

Tiv-Model: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

Today's objective

"To gain feedback from engineering industry veterans on their perception of the Tiv-Model"

- Tiv-Model is a research driven product lifecycle design methodology
- Quantitative and qualitative evidence required

Tiv-Model: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

Today's objective

"To gain feedback from engineering industry veterans on their perception of the Tiv-Model"

- Tiv-Model is a research driven product lifecycle design methodology
- Quantitative and qualitative evidence required

SMeSTech ★
Space Mechatronic Systems Technology

Tiv-Model: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

What's in the Tiv-Model?

Empirically validated
Uses t-test case study and validation tool

Follows academic recommendations
Modern and classic literature "best practice"

Mitigates industry challenges and concerns
Designed for industry, breaks adoption barrier

Novice friendly
Techniques that help integrate non-veteran engineers

SMeSTech ★
Space Mechatronic Systems Technology

Tiv-Model: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

Tiv-Model

Design Novice friendly
- Ease of learning
- Ease of use
- C-QuARK problem solving strategy

Industry Adoptability focus
- Provides proof of effectiveness
- Modular implementation
- Transparency of information

Methodology Classic and modern research
- Applied design process
- "Best of" existing models
- Requirements and specifications

Space Iterative design validation
- Aerospace milestones
- Post delivery considerations
- Feasibility studies

Complex Systems Simplifies complex issues
- Config management/PLM integration
- Software component
- Knowledge Database

V & V Verified and Validated
- Validation Square tool
- Qualitative and quantitative studies
- Verification process outlined

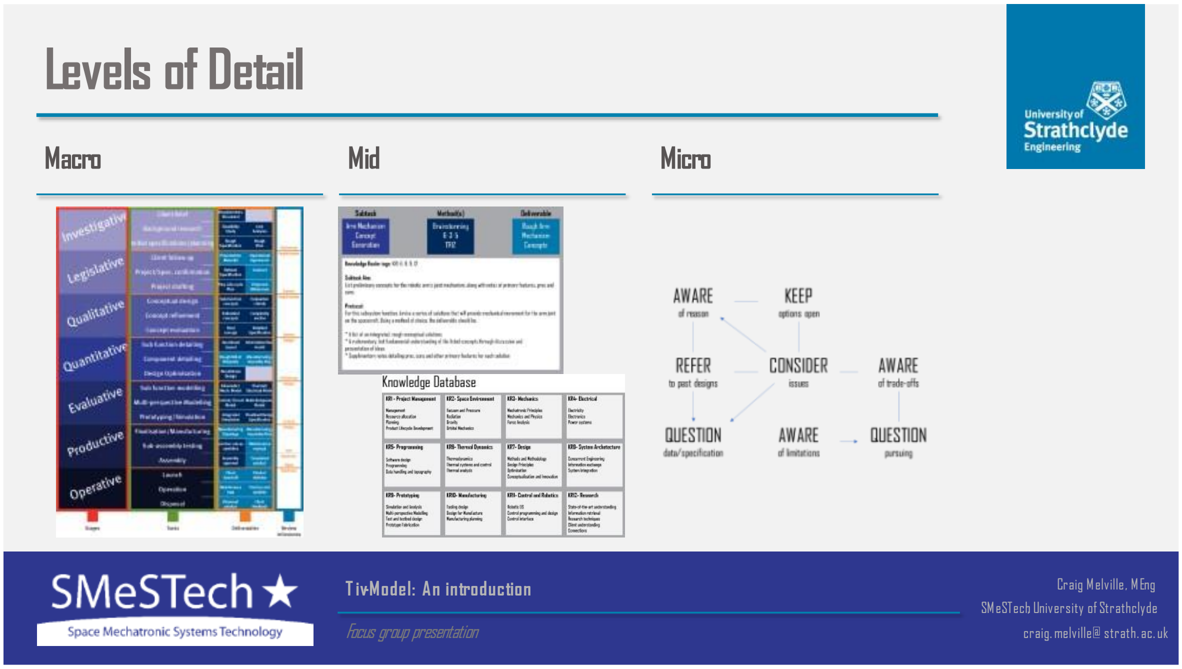
Investigative	Client Brief	Requirements Document		
	Background research	Feasibility Study	Cost Analysis	
	Initial specifications/planning	Rough Specification	Rough Plan	Preliminary Requirements
Legislative	Client follow-up	Presentation Material	Operational Agreement	
	Project/Spec. confirmation	Refined Specification	Contract	
	Project drafting	Proj. Life-cycle Plan	Projected Milestones	System Requirements
Qualitative	Conceptual design	Sub-function concepts	Evaluation criteria	
	Concept refinement	Embodied concepts	Complexity anchor	
	Concept evaluation	Final concept	Detailed Specification	System Design
Quantitative	Sub function detailing	Functional Layout	Information flow model	
	Component detailing	Rough Bill of Materials	Manufacturing/ Assembly Req.	
	Design Optimisation	Penultimate Design		Preliminary Design
Evaluative	Sub function modelling	Kinematic/ Mech. Model	Thermal/ Electrical Model	
	Multi-perspective Modelling	Control/ Circuit Model	Multi-Perspective Model	
	Prototyping/Simulation	Integrated Simulation	Finalised Design Specification	Critical Design
Productive	Finalisation/Manufacturing	Manufacturing Drawings	Manufacturing/ Assembly Plan	
	Sub-assembly testing	Function sub-assemblies	Maintenance manual	Test Readiness
	Assembly	Assembly approval	Completed product	Flight Readiness
Operative	Launch	Client hand-off	Product delivery	
	Operation	Maintenance logs	Patches and updates	
	Disposal	Disposed product	Client feedback	

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Levels of Detail

Macro

Mid

Knowledge Database

KR1 - Project Management Management Resource allocation Planning Product Lifecycle Development	KR2- Space Environment Vacuum and Pressure Radiation Gravity Orbital Mechanics	KR3- Mechanics Mechatronic Principles Mechanics and Physics Force Analysis	KR4- Electrical Electricity Electronics Power systems
KR5- Programming Software design Programming Data handling and topography	KR6- Thermal Dynamics Thermodynamics Thermal systems and control Thermal analysis	KR7- Design Methods and Methodology Design Principles Optimisation Conceptualisation and Innovation	KR8- System Architecture Concurrent Engineering Information exchange System integration
KR9- Prototyping Simulation and Analysis Multi-perspective Modelling Test and testbed design Prototype Fabrication	KR10- Manufacturing Tooling design Design for Manufacture Manufacturing planning	KR11- Control and Robotics Robotic OS Control programming and design Control interface	KR12- Research State-of-the-art understanding Information retrieval Research techniques Client understanding Connections

Micro

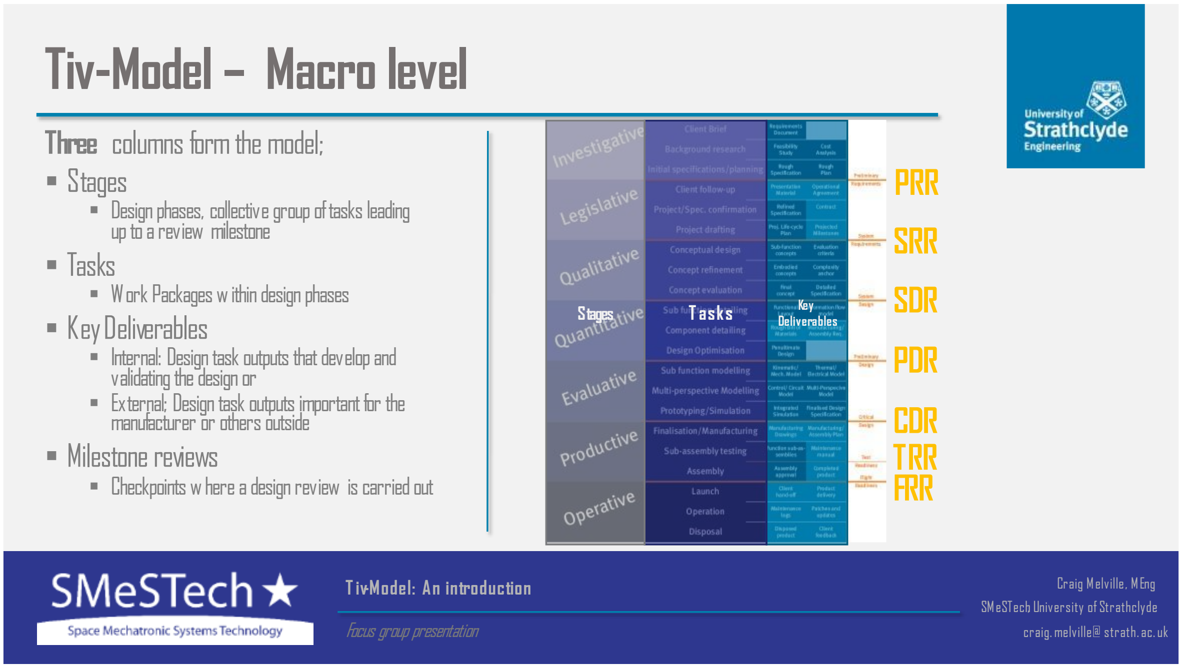
AWARE of reason
KEEP options open
REFER to past designs
CONSIDER issues
AWARE of trade-offs
QUESTION data/specification
AWARE of limitations
QUESTION pursuing

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Tiv-Model – Macro level

Three columns form the model;

- Stages
  - Design phases, collective group of tasks leading up to a review milestone
- Tasks
  - Work Packages within design phases
- Key Deliverables
  - Internal: Design task outputs that develop and validating the design or
  - External: Design task outputs important for the manufacturer or others outside
- Milestone reviews
  - Checkpoints where a design review is carried out

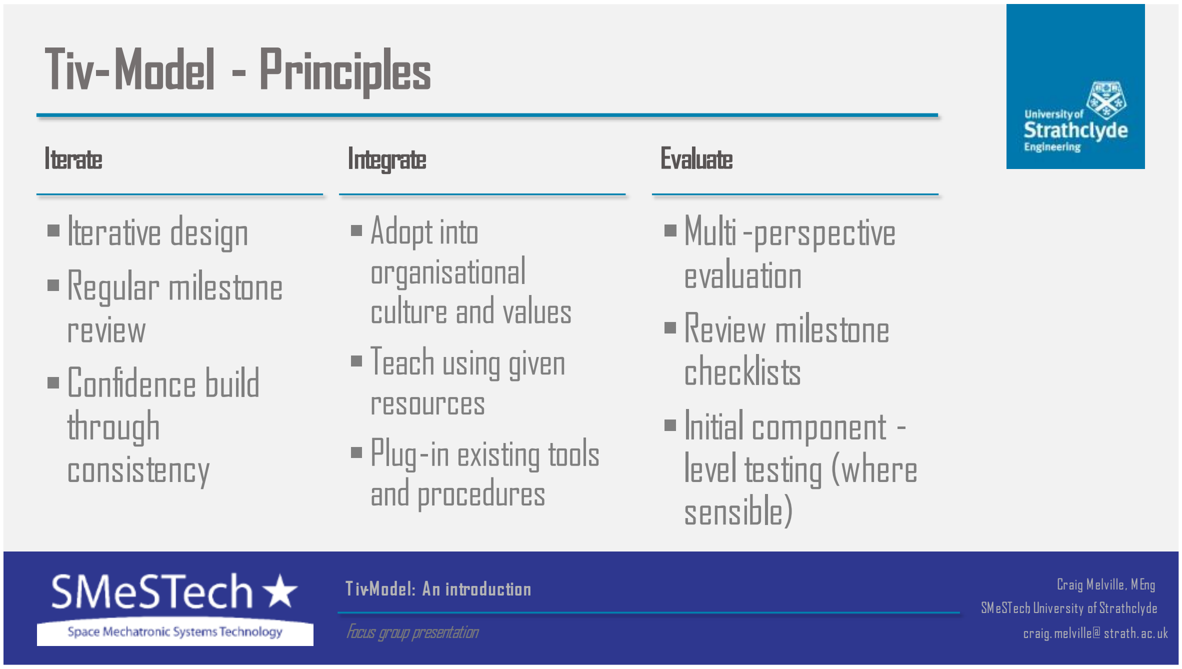
University of Strathclyde Engineering

SMeSTech★ Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Tiv-Model - Principles

Iterate	Integrate	Evaluate
Iterative design Regular milestone review Confidence build through consistency	Adopt into organisational culture and values Teach using given resources Plug-in existing tools and procedures	Multi-perspective evaluation Review milestone checklists Initial component-level testing (where sensible)

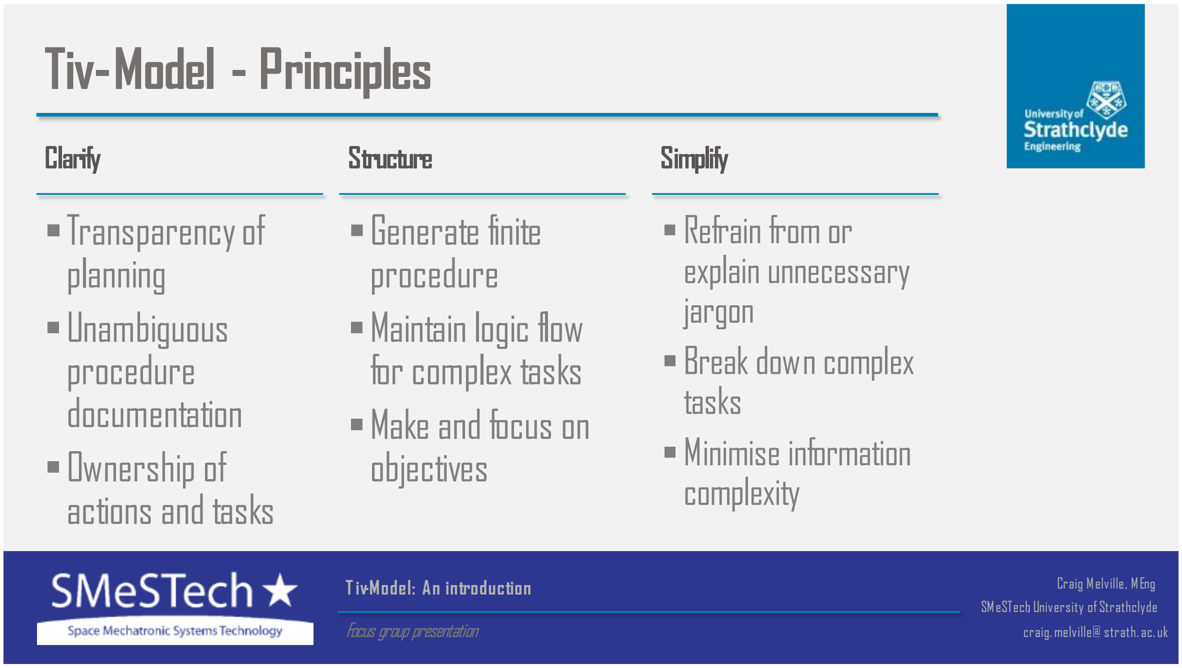
University of Strathclyde Engineering

SMeSTech★ Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Tiv-Model - Principles

University of Strathclyde Engineering

Clarify

- Transparency of planning
- Unambiguous procedure documentation
- Ownership of actions and tasks

Structure

- Generate finite procedure
- Maintain logic flow for complex tasks
- Make and focus on objectives

Simplify

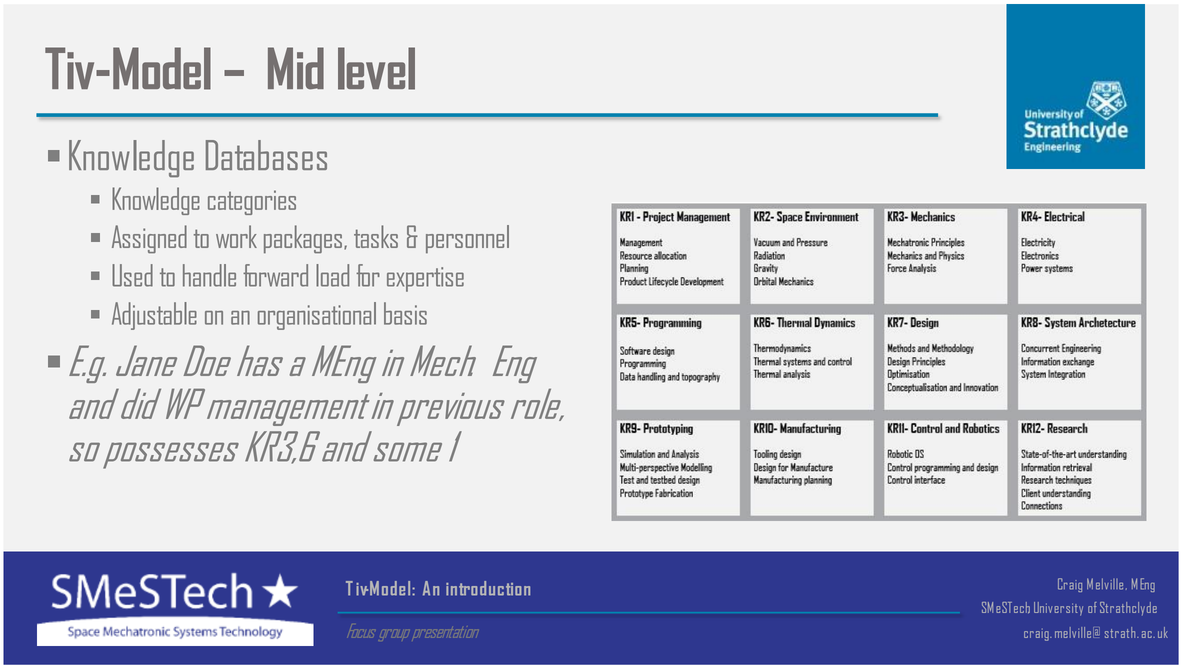
- Refrain from or explain unnecessary jargon
- Break down complex tasks
- Minimise information complexity

SMeSTech★ Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Tiv-Model – Mid level

University of Strathclyde Engineering

- Knowledge Databases
  - Knowledge categories
  - Assigned to work packages, tasks & personnel
  - Used to handle forward load for expertise
  - Adjustable on an organisational basis
- *E.g. Jane Doe has a MEng in Mech Eng and did WP management in previous role, so possesses KR3,6 and some 1*

KR1 - Project Management Management Resource allocation Planning Product Lifecycle Development	**KR2- Space Environment** Vacuum and Pressure Radiation Gravity Orbital Mechanics	**KR3- Mechanics** Mechatronic Principles Mechanics and Physics Force Analysis	**KR4- Electrical** Electricity Electronics Power systems
KR5- Programming Software design Programming Data handling and topography	**KR6- Thermal Dynamics** Thermodynamics Thermal systems and control Thermal analysis	**KR7- Design** Methods and Methodology Design Principles Optimisation Conceptualisation and Innovation	**KR8- System Archetecture** Concurrent Engineering Information exchange System Integration
KR9- Prototyping Simulation and Analysis Multi-perspective Modelling Test and testbed design Prototype Fabrication	**KR10- Manufacturing** Tooling design Design for Manufacture Manufacturing planning	**KR11- Control and Robotics** Robotic OS Control programming and design Control interface	**KR12- Research** State-of-the-art understanding Information retrieval Research techniques Client understanding Connections

SMeSTech★ Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

Tiv-Model – Mid level

Subtasks within a work package that follow procedure

Subtasks are predefined protocol; methods are pre-recommended but can be replaced/removed in planning phases

Sub-function modelling

Subtask	Methods	Deliverable
Elec. part creation	ELC300, ELC300A	Draft Family-tree document

Task number: 00334-11

KDs: KR1-4, 8, 9, 13

Potential assignees: Jane Doe, John Smith

Subtask aim:

Create primary sub-assembly groups in Windchill and IFS and setup BoM

General process:

Follow procedure in document ELC300, using ELC300A as a template. Create sub-assemblies for the numbers present in document...

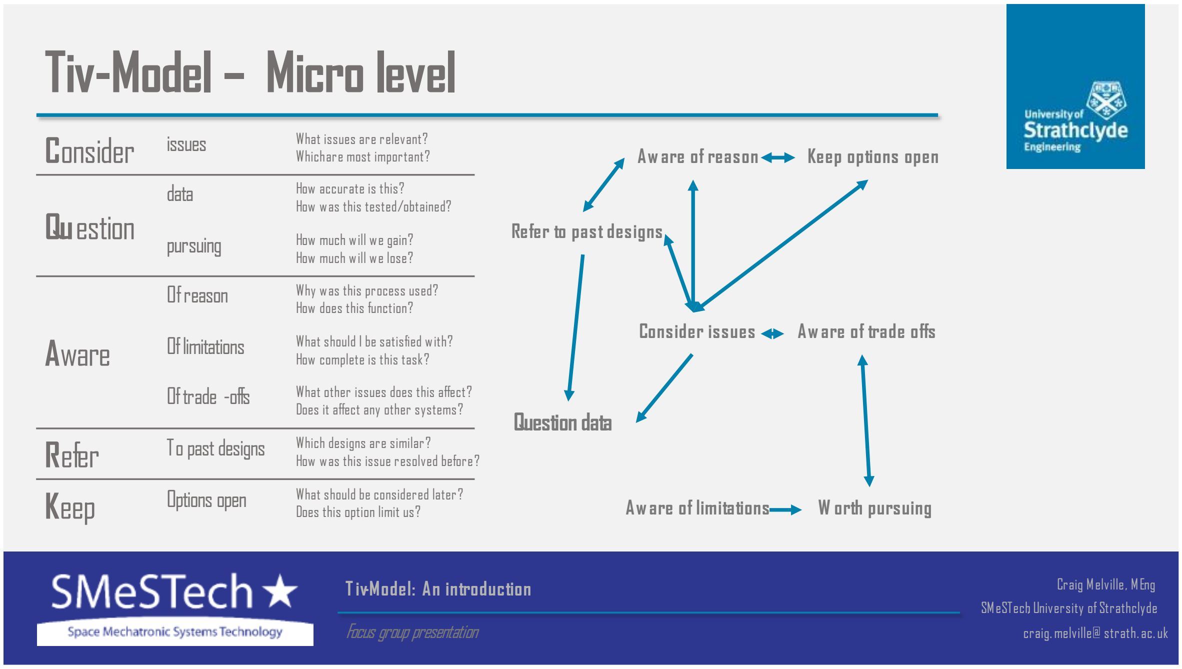
University of Strathclyde Engineering

SMeSTech
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Tiv-Model – Micro level

Consider	issues	What issues are relevant? Whichare most important?
Question	data	How accurate is this? How was this tested/obtained?
	pursuing	How much will we gain? How much will we lose?
Aware	Of reason	Why was this process used? How does this function?
	Of limitations	What should I be satisfied with? How complete is this task?
	Of trade-offs	What other issues does this affect? Does it affect any other systems?
Refer	To past designs	Which designs are similar? How was this issue resolved before?
Keep	Options open	What should be considered later? Does this option limit us?

Aware of reason ↔ Keep options open
Refer to past designs
Consider issues ↔ Aware of trade offs
Question data
Aware of limitations → Worth pursuing

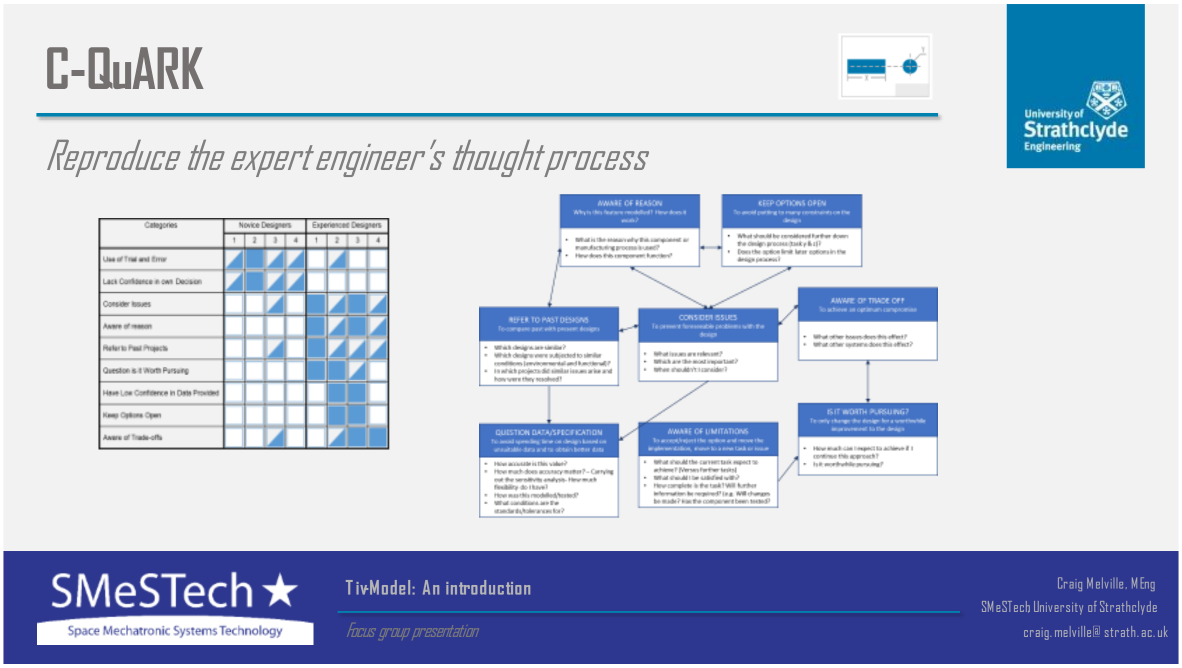
University of Strathclyde Engineering

SMeSTech
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



C-QuARK

University of Strathclyde Engineering

Reproduce the expert engineer's thought process

Categories	Novice Designers				Experienced Designers			
	1	2	3	4	1	2	3	4
Use of Trial and Error	◢	🟦	◢	◢		◢		
Lack Confidence in own Decision	◢	🟦	◢	◢				
Consider Issues			◢		🟦	◢	🟦	◢
Aware of reason					🟦	◢	🟦	◢
Refer to Past Projects			◢		🟦	◢	◢	◢
Question is it Worth Pursuing					🟦	🟦	◢	
Have Low Confidence in Data Provided						🟦	🟦	
Keep Options Open						🟦	🟦	
Aware of Trade-offs			◢			◢	🟦	🟦

AWARE OF REASON
Why is this feature modelled? How does it work?
- What is the reason why this component or manufacturing process is used?
- How does this component function?

KEEP OPTIONS OPEN
To avoid putting to many constraints on the design
- What should be considered further down the design process (task y & z)?
- Does the option limit later options in the design process?

REFER TO PAST DESIGNS
To compare past with present designs
- Which designs are similar?
- Which designs were subjected to similar conditions (environmental and functional)?
- In which projects did similar issues arise and how were they resolved?

CONSIDER ISSUES
To prevent foreseeable problems with the design
- What issues are relevant?
- Which are the most important?
- What shouldn't I consider?

AWARE OF TRADE OFF
To achieve an optimum compromise
- What other issues does this effect?
- What other systems does this effect?

QUESTION DATA/SPECIFICATION
To avoid spending time on design based on unsuitable data and to obtain better data
- How accurate is this value?
- How much does accuracy matter? – Carrying out the sensitivity analysis- How much flexibility do I have?
- How was this modelled/tested?
- What conditions are the standards/tolerances for?

AWARE OF LIMITATIONS
To accept/reject the option and move the implementation, move to a new task or issue
- What should the current task expect to achieve? (Verses further tasks)
- What should I be satisfied with?
- How complete is the task? Will further information be required? (e.g. Will changes be made? Has the component been tested?)

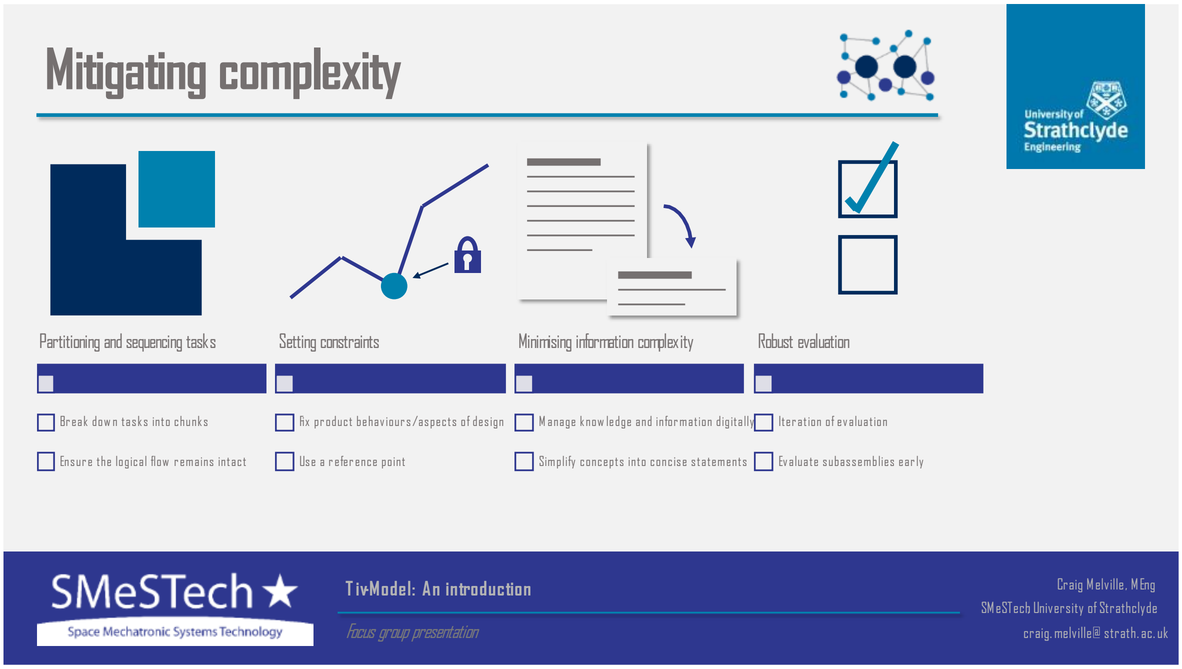
IS IT WORTH PURSUING?
To only change the design for a worthwhile improvement to the design
- How much can I expect to achieve if I continue this approach?
- Is it worthwhile pursuing?

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Mitigating complexity

University of Strathclyde Engineering

Partitioning and sequencing tasks
☐ Break down tasks into chunks
☐ Ensure the logical flow remains intact

Setting constraints
☐ Fix product behaviours/aspects of design
☐ Use a reference point

Minimising information complexity
☐ Manage knowledge and information digitally
☐ Simplify concepts into concise statements

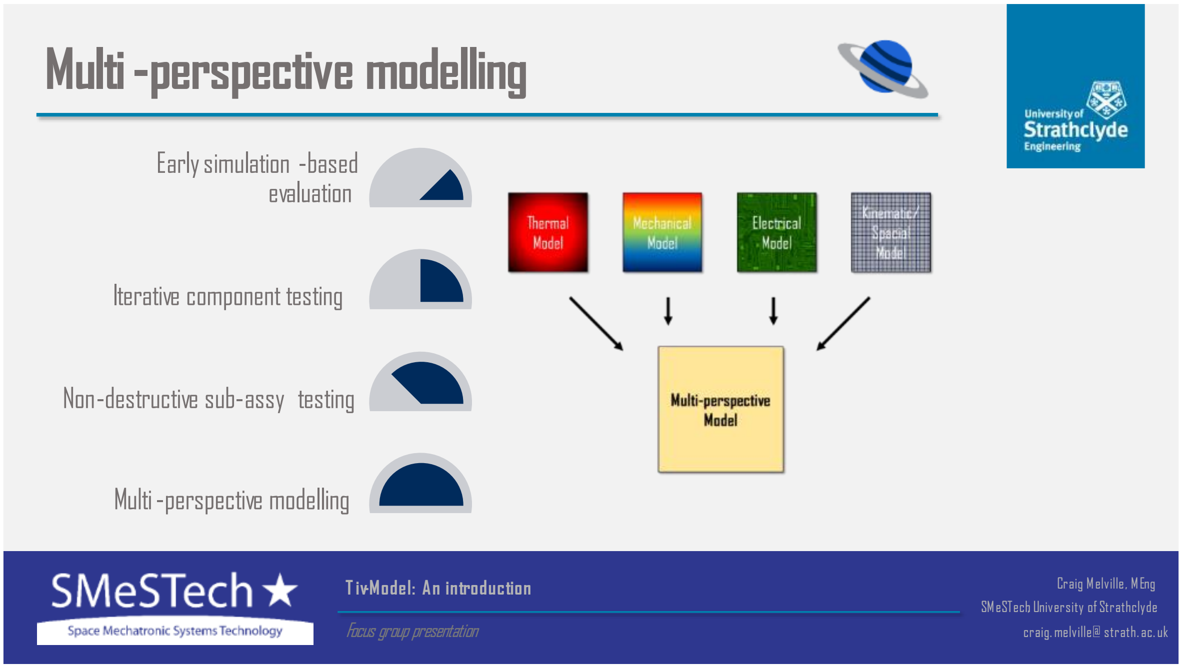
Robust evaluation
☐ Iteration of evaluation
☐ Evaluate subassemblies early

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Multi -perspective modelling

Early simulation -based evaluation

Iterative component testing

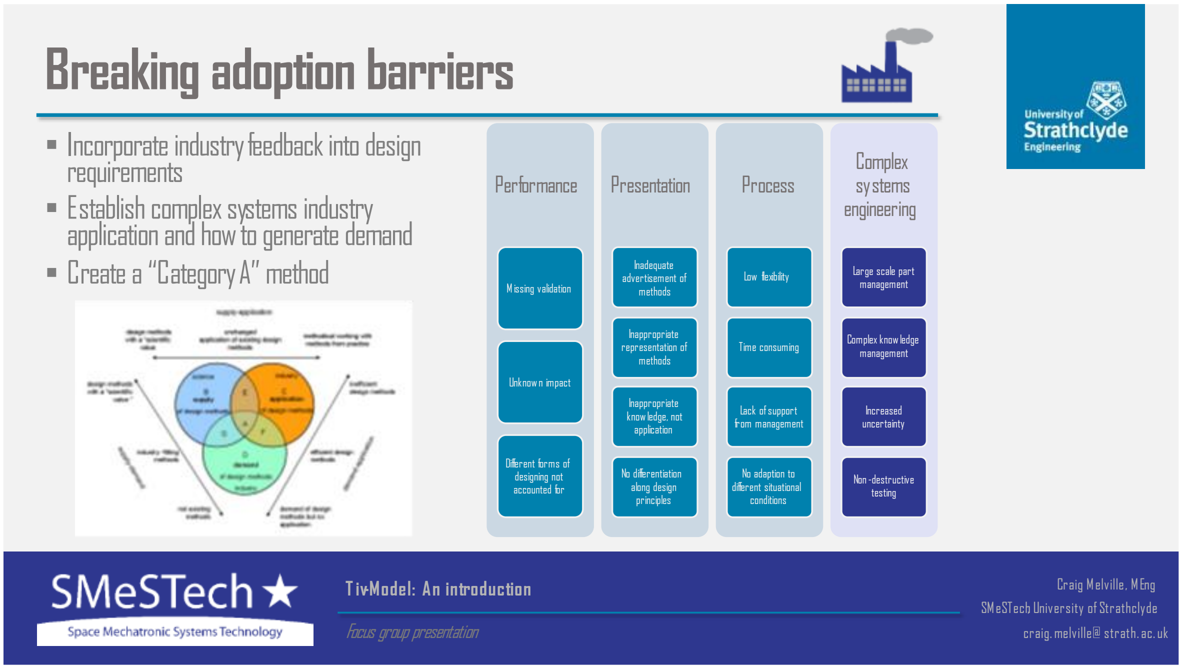
Non-destructive sub-assy testing

Multi -perspective modelling

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Breaking adoption barriers

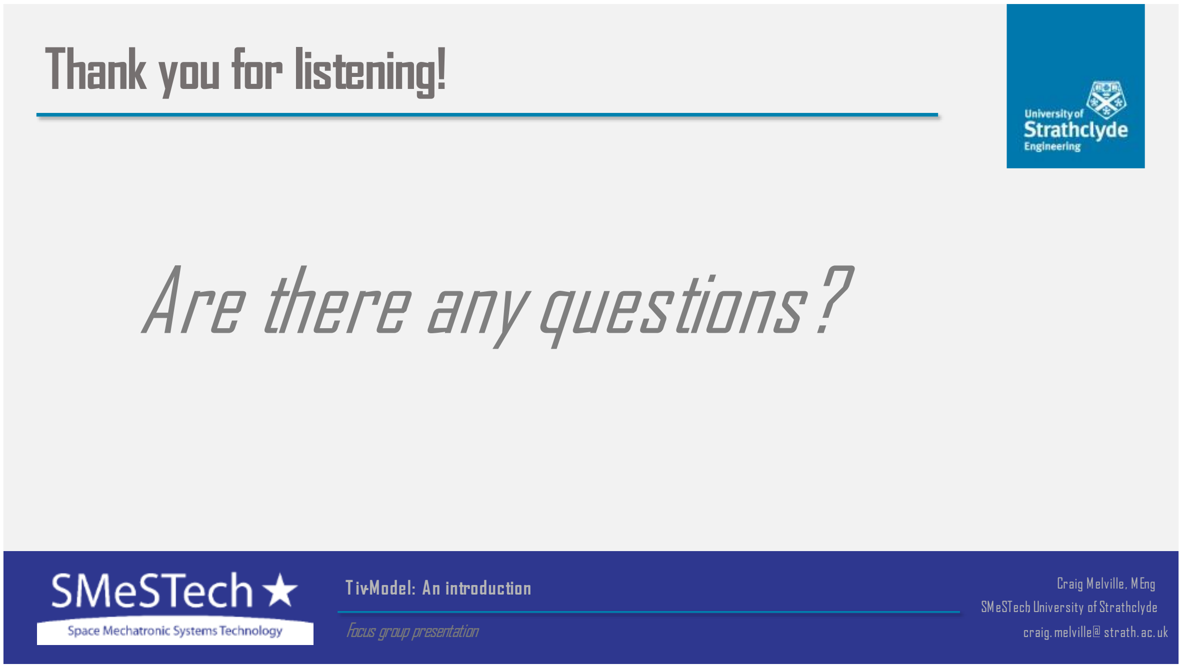
- Incorporate industry feedback into design requirements
- Establish complex systems industry application and how to generate demand
- Create a "Category A" method

Performance	Presentation	Process	Complex systems engineering
Missing validation	Inadequate advertisement of methods	Low flexibility	Large scale part management
Unknown impact	Inappropriate representation of methods	Time consuming	Complex knowledge management
Different forms of designing not accounted for	Inappropriate knowledge, not application	Lack of support from management	Increased uncertainty
	No differentiation along design principles	No adaption to different situational conditions	Non-destructive testing

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk



Thank you for listening!

University of Strathclyde
Engineering

Are there any questions?

SMeSTech★
Space Mechatronic Systems Technology

TivModel: An introduction

Focus group presentation

Craig Melville, MEng
SMeSTech University of Strathclyde
craig.melville@strath.ac.uk

SMeSTech★
Space Mechatronic Systems Technology

University of Strathclyde, Glasgow

Contact:
Prof. Xiu T Yan
x.yan@strath.ac.uk

B.iii Focus group study survey results

D = Disagree

SD = Somewhat Disagree

NS = Not sure

SA = Somewhat Agree

A = Agree

Category	Question	D	SD	NS	A	SA
I believe that, if implemented within an organisation, Tiv-Model could…	Lower the overall cost of the design process			4		
	Speed up aspects of the design process			2	2	
	Increase the quality of the end-product				3	1
	Reduce the amount of rework performed through the design process			1	3	
	Improve adherence to critical design procedures			2	2	
	Aid in the effective management of personnel resource		2	1		1
I believe that Tiv-Model, in theory…	Addresses the needs of industry		1	1	2	
	Is friendly towards novice engineers				2	2
	Is a viable alternative to other design methodologies			1	3	
	Needs extensive work before being utilised		1	1	1	1
	Is complex to grasp		1		3	
	Misses key information			2	2	
This focus group session was…	In a relaxed atmosphere					4
	An appropriate length of time					4
	Well organised				1	3
	Educational				2	2
	Interesting				1	3