A Graphical Framework for Component Selection in Mechatronic Design of Robotic Systems

By

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This Thesis is submitted to the Department of Design, Manufacture and Engineering Management, University of Strathclyde, for the degree of Doctor of Philosophy.

Declaration of Authenticity and Author's Rights

AUTHOR'S DECLARATION

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.

Signed: Scott Brady Date: 09/05/2020

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Publications

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Abstract

The successful function of complex engineering systems, particularly those which provide a dynamic performance capability to a system, is usually largely dependent on the correct specification and selection of components to be used in that system. Whilst material selection and part design for housings, etc. are critical tasks, in any system required to provide some physical capability (displacement, pressure, measurement capability, etc.) it is entirely likely that *components selected* to achieve this - such as motors, bearings, etc. - will be instrumental in defining the extent to which performance goals are met for that system.

Unlike material selection and part design tasks, there are noted to be markedly fewer strategies and methods to support engineers through successful and effective completion of this task. Despite acknowledgement of the absolute significance of this task and the outputs it yields in many design methodologies, academic literature which explores this topic is found to be limited. Commercial solutions to the problem are also found to have various issues, as is explored in this project. The components selected in a system have an extremely large role to play in the capability of the system to perform as needed, therefore providence of solutions which improve the effectiveness of engineers in effective completion of this task are argued to be of upmost significance.

At its core, this thesis contributes a framework to support component selection in the design of mechatronic actuators, supporting a process where step-by-step guidance is offered through concept and embodiment design stages. Underlying the core framework and its process guidance, a number of other novel methods are proposed as a means to enhance effectiveness and efficiency in approaching and completing discrete tasks within the overall selection procedure. In this thesis, particular focus is given to the use of a novel graphical method of conveying component performance criteria in a way which supports informative and intuitive interrogation of the information they present.

Application of the framework is completed in the context of mechatronic actuators utilised in robotic sub-systems. The contributed framework is assessed through 3 separate case studies undertaken to assess the effectiveness of this approach. These case studies vary in use case and requirement, allowing the adaptability of the proposed approach to be assessed. From these case studies, analysis takes place through discussion, simulation, and physical testing of the developed systems, allowing for a wealth of qualitative and quantitative information to be gathered upon which assertions can be made. Discussion is presented surrounding the overall performance, and conclusions are delivered to provide a verdict on the interpretations of the solution's effectiveness.

“Do or do not, there is no try”.

(Yoda, A long time ago…)

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1.0 Introducing the Subject Area

1.1 Overview

There are a number of crucial systems, features, and principles without which mechatronic and robotics systems will not function to any degree of usefulness. These instances range across the intangibles of the underlying control theory, to the readily observable actuation packages used to drive actuators in rigid link robotic systems, for example. Any mechatronic system which elicits a physical movement, irrespective of purpose, material composition, age, etc. requires some form of actuation to achieve this.

Solutions for actuation components are massively diverse, and this enormous range of candidate solutions to often presents a complex and overwhelming task in engineering design (Harmer et al., 1998). Presently, it is perceived that many component selection strategies rely on individual selection processes being adopted for different component types; motors are selected using motor selection approaches (Hughes, 2013b), and the same is true of bearings , transmission systems (Ewert, 1997), etc. It is considered that these selection processes also often lack specific guidance. Additional comment has been made on the paradigmatic ("we have done it this way before, so we will continue to do it that way") nature of decision-making in engineering design tasks (Huber et al., 1997a) (Ashby, 1992), where component selection has specifically been noted to have succumb to this issue too (Cuttino et al., 2010). Issues surrounding awareness of solutions are also commonly voiced (Hicks et al., 2002). As will be explored in more detail in section 2.5, seminal publication in this field has drawn attention to a range of issues which are evidenced to affect component selection tasks (Harmer et al., 1998) (Vogwell & Culley, 1991), with a range of more modern examples demonstrating the present day impacts. Whilst existing tools and processes have delivery of functioning solutions, there are still demonstrably issues evident in modern application.

The effects of changes in engineering projects are well-documented in terms of their causes and in terms of the effects (Siddiqi et al., 2011). Therefore, decisions such as those made in component selection, are known to have large impacts if change is required later. With a task such as component selection these costs can manifest as labour costs and the need to purchase *additional* components to meet a specification. Issues like this are noted to affected projects of all types. Conversely, some issues, such as high costs of low volume products (Harmer et al., 1998), are noted to be adversely affected by producers not being well-enabled with component selection aids.

The work presented in this thesis has sought to establish a solution to support component selection during the design of mechatronic actuators, particularly as it pertains to those used in actuation of robotic systems. In doing so, it is sought to replace what is currently identified to often be an ad hoc process with a rigorous process, which is more formalised and is supported in a logical, step-wise manner.

At the highest levels of granularity related to this selection problems, engineering design literature advocates the completion of engineering design processes supported by new tools and methods to achieve improved outputs:

> "Solution principles or designs based on traditional methods are unlikely to provide optimum answers when new technologies, procedures, materials, and also new scientific discoveries, possible in new combinations, hold the key to better solutions." – (page 161, Bietz, 2007).

It has previously been observed how engineering design tasks are often blighted by several key issues, generally:

- "the right idea rarely comes at the right moment, since it cannot be elicited and elaborated at will;
- The result depends on individual talent and experience;
- There is a danger that solutions will be circumscribed by preconceived ideas based on one's special training and experience" (page 54, Pahl & Beitz, 2007).

Each of the aforementioned points are considered to corroborate some of the high-level issues identified in component selection tasks. Systematic processes are discussed to address such issues (S. Pugh, 1990) (Gerhard Pahl et al., 2006) by providing greater repeatability and quality to the results produced in engineering design. The issue of bias affecting results is something also echoed by other authors, most notably in selection of materials (Ashby, 2005), but specific mention in the context of selecting engineering components is also made (Vogwell, 1990).

In more specific literature, component selection is known to be a crucial task in any engineering design process. Reputable and seminal mechatronic design methodologies (Zante & Yan, 2010) (Zheng et al., 2017) (P. Hehenberger et al., 2010), guidelines (Gausemeier & Moehringer, 2002a), models (I. Graessler et al., 2018) (Iris Graessler & Hentze, 2020), and frameworks (Kernschmidt et al., 2018) are shown to specifically cite component selection as a key task, evidencing acknowledgement of its importance within the design activity. Component selection is mentioned at the same granularity as other crucial tasks, such as concept generation; concept evaluation; materials selection; etc. Noticeably, these tasks are known to have a wealth of tools, methods, and approaches to support their completion; for example, morphological charts, concept scoring matrices, Granta selector, respectively. It is therefore surprising that a greater range of established solutions do not exist in academic literature as a means to support component selection activities in engineering design activities, given there is an acknowledgement of its significance.

Several instances have been encountered where high-level guidance particular to the selection of varying components is offered in core mechatronic and mechanical engineering texts (Bolton, 2015) (Siciliano & Khatib, 2016). Similarly, component specific high-level guidance is noted in handbooks and manuals specific to particular component types: motors (Hughes, 2005) or transmissions (Ewert, 1997), for example. It is noted that these examples offer only very general guidance which is not particular to some of the more idiosyncratic issues encountered in component selection tasks and clearly does not account for design requirements of actuators within specific contexts.

Solutions are also encountered which propose strategies on how component selection should be approached with more detail and without specific allusion to a particular component type (Carlson, 1996) (Vogwell & Culley, 1991), but despite better granularity there is still an absence of guidance on specifics information which should be presented. There is also an obvious omission of methods which can support such a task. As some of these strategies are now dated, many opportunities now present themselves where technological developments may facilitate the task being undertaken more effectively with new methods and tools; most notably, the more extensive use of computers and the internet, where some developments have already been proposed (Madden & Filipozzi, 2005).

Specific methods and propositions for representing information are sporadically encountered, including more detailed step-wise selection approaches (Cuttino et al., 2010) (Hicks et al., 2002). The use of taxonomy (Zupan et al., 2002) and categorisation (Poole & Booker, 2011) of component information to aid selection by promoting easier access to the information of interest has also been explored. A range of solutions already presented commercially are also noted to be available to engineers, which section 2.5.2. examines with in detail.

Despite good developments and exploration of novel methods and tools to assist component selection, it is considered that there is a great deal of room to build on these efforts. It is noted that existing strategies and approaches used in this domain do not support selection from early stages through to specification of a specific solution. There are also limited methods and tools for effectively communicating quantitative and qualitative information about candidate components, despite its importance being acknowledged in mechatronic design tasks (Habchi & Barthod, 2016). This being so, it is clear that an opportunity exists not only to propose a new rigorous and methodical solution to support component selection processes, but also to develop new methods and tools to assist users in completing selection procedures more effectively.

Component selection is acknowledged to be an important task in the overall engineering design activity, whilst specific literature on component selection coupled with various commercial solutions also demonstrates the demand and need for support being provided to engineers in this task. Despite the presence of academic and commercial solutions, there are also observed issues which are noted to be ratified in other publication. These themes are explored in greater detail in chapter 2 of this thesis, and their significance further analysed.

1.2. Hypotheses

This work proposes that a more systematic approach to component selection can be introduced to support reaching a solution to meet pre-defined requirements of a system. This proposition is formalised in the following hypothesis:

> A systematic process to guide component selection tasks can be implemented which supports selection of key components required to enable solutions to meet their pre-defined requirements

An additional hypothesis has been added based on review of literature, which postulates exploring a particular new method of interrogating information to support this systematic process. This is documented further throughout chapter 2, but in the interests of providing both hypotheses together, this additional hypothesis is presented below:

> It will be possible to utilise graphical methods to represent component performance information in a format which is suitable for interrogation to make component selection choices.

These two hypotheses bring together the key elements of what this work seeks to achieve: the development of a solution which provides a methodical means of approaching a task which can often define the success of a project; and, exploration of new tools which are leveraged *by* any methodical solution, so that engineers are supported in returning high quality solutions.

1.3. Project Purpose

Motivation to explore this subject area had initially been developed from experience, where it had been noticed that existing solutions were often accompanied by a range of issues. Review of pertinent literature and existing solutions, as detailed in the previous section and expanded upon in chapter 2, helped to corroborate many of these observations.

Fundamentally, this provided the researcher with clarification towards what the prescriptive actions should be in order to provide a proposed solution to the issues identified. Succinctly, has been defined as a project aim, though terms such as "mission" or "vision" (Duffy & Donnell, 1998) are also noted to be used as analogous descriptions.

1.3.1. Project Aim

The overall goal of the project is captured by the following project aim:

> **To develop a solution to support engineers in methodically completing component selection tasks when designing mechatronic actuators for use in robot sub-systems.**

Understanding of existing approaches to component selection will be developed and knowledge of how they can be improved will be explored. Approaches taken in other works and in other engineering disciplines will also be reviewed as a means to inspire.

This work should not be considered an optimiser for component selection at this stage in development. It is the first step in understanding a new solution proposed to enable completion of component selection in mechatronic systems, and how it may help to remove some obstacles currently met. It may eventually be a better approach **after further development**.

1.4. Research Question

Section 1.1. has drawn attention to themes in literature supporting the notion that there is utility and an interest in the development of a solution to support methodical approaches to component selection tasks. This discourse has included mention of novel ideas already considered in literature, which may also provide scope to build new and novel tools to support the methodical solution to be documented in this thesis.

Section 1.3. has detailed that the project should aim to develop a solution to support component selection. As a means to assess the effectiveness of the solution, the question this research will seek to answer is:

> **How effective is the proposed solution in supporting methodical component selection to facilitate selection of components to meet functional system requirements?**

Providence of an answer to this question will illuminate the manners in which the solution developed is effective (and ineffective) in enabling mechatronic actuator design, and a number of insights about this approach's idiosyncrasies will consequently be understood. Consequently, other information of interest will also developed regarding this contribution's place in literature and the significance of the work to other interested parties. Fundamentally, attempting to answer this question will allow clarity to be gained regarding whether the proposed approach allows defined system requirements to be met.

1.4.1. Objectives

To assist answering the research question resolutely, objectives have been fomented to generate applicable answers as milestones to achieving an overall answer to the question posed. These objectives are as follows:

- Objective 1: Develop understanding of state of the art in the context of the subject matter; i.e. state of the art in robotic actuation, mechatronic design methodologies, and component selection strategies, methods, and tools;

- Objective 2: Develop specification of traits that an effective solution for supporting component selection must possess;

- Objective 3: On the basis of the specified requirements, develop a solution to meet these requirements;

- Objective 4: Expose the solution to typical use cases in order to assess its functionality as applied in these typical situations such that the effectiveness of the solution can begin to be understood; and,

- Objective 5: Analyse development and application of proposed solution to provide clear assessment of the effectiveness of the solution in delivering functional systems.

1.5. Research boundary

The focus of this thesis will be on mechatronic design of actuators. Specifically, those which are utilised in robotic sub-systems; joint actuators, actuators in end of arm tooling, etc. Components and guidance presented is particular to application in this domain, at present maturity of the solution proposed in this thesis. It is important to understand what is meant by some of these terms in the context of the boundaries of this project. The solution proposed must facilitate dealing with the components defined to be of significance within the boundary of this study, and it must facilitate selection taking place during typical component selection tasks as they are undertaken in mechatronic design.

1.5.1. Mechatronics and Robotics

A succinct and clear definition of the term mechatronics is offered by Bradley *et al*.:

> *"Mechatronics is concerned with the bringing together and integration of certain key areas of technology, particularly:*

- *Sensors and instrumentations systems;*
- *Embedded microprocessor systems;*
- *Drives and actuators; and,*
- *Engineering design." (D. A. Bradley et al., 1993)*

This definition is corroborated closely by numerous other key authors in this field (Billingsley, 2006) (Bolton, 2015) (Alciatore & Histand, 2012) (Jablonski, 2011) (D. Bradley & Russell, 2010).

A robotic system conforms to the intelligent machine definition from mechatronics. Within the larger field of mechatronics, robotic systems are described as a "narrow subset" of mechatronics (Page 6, Billingsley, 2006). Billingsley and Bolton's have produced seminal publication on mechatronics, enabling clarification that it is reasonable to describe a robot as a type mechatronic system. To ensure consistency, the robot actuators are described as *mechatronic actuators* herein.

1.5.2. Mechatronic Actuators

Key literature in the field has described mechatronic *systems* as outlined in figure 1 (Page 449, Gerhard Pahl et al., 2006), describing how actuators can be considered as a sub-element within a mechatronic system's overall architecture. The focus in this study will be on selection for the actuators used in a mechatronic system; i.e. the physical engineering components used to drive the system. The image provided in figure 1 highlights the types of components of interest in the specific context of robot actuators (the type of mechatronic actuator of particular interest in this work); bearings, motors, transmissions, and brakes. Sensors, motor drivers, microcontrollers, etc. are not considered relevant at this stage. The highlighted region in figure 2 clarifies the components of interest within the actuation arrangement.

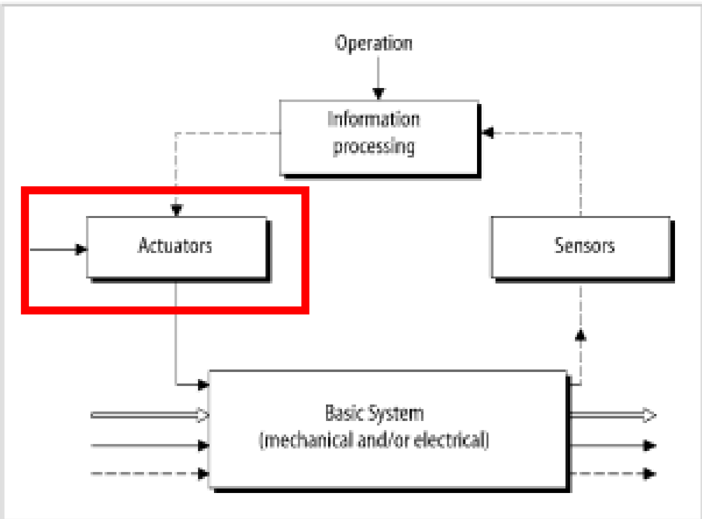

Figure 1: Key parts of a mechatronic system (Page 449, Gerhard Pahl et al., 2006). Red highlight added by Scott Brady

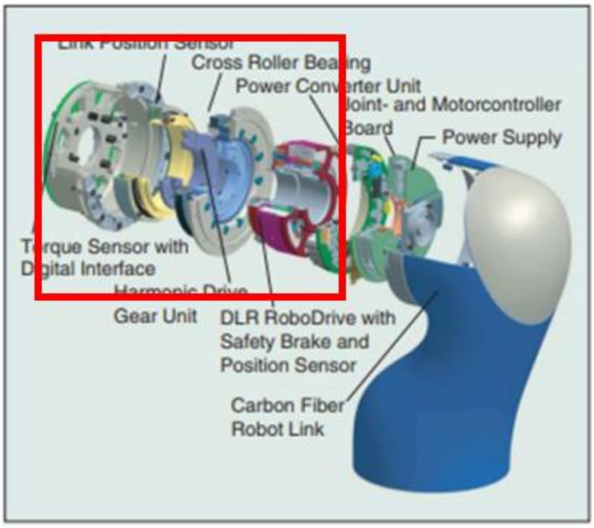

Figure 2: Area of focus in context of robot joint actuation design.

1.6. The Research Design

This study seeks to understand the effectiveness of applying a selection solution to achieve functional outcomes and how it relates to existing engineering design strategies. Capture of qualitative and quantitative data will best assist in assessment and answering the research question.

It is considered that this work follows a pragmatist research philosophy, whereby action is required to produce solutions to assist in resolution (Elkjaer & Simpson, 2011) as a means to provide credible, well-founded knowledge to improve circumstances (Kelemen & Rumens, 2008). Qualitative and quantitative data types are expected to be evident in this type of study, and should provide the objective and subjective inputs needed for assessments to be made in answering the research question, and in validating or refuting the hypotheses. Whether the performance of the selected components meets specified requirements can be verified with quantitative measurement by assessing the performance achieved by solutions, whilst “why” and “how” type information can be generated by the qualitative data collection developed during application of the solution during test studies. This enables evaluation of the solution proposed, facilitating better understanding of how it works and its effectiveness in the instances where it is assessed.

1.6.1. Study Type

The greatest interest in this study lies in establishing a solution and developing an initial understanding of the effectiveness solution proposed in producing solutions to meet system requirements. Evaluative studies are used to assess the successfulness or utility of something (SAGE, 2019) (Payne & Payne, 2004). The significance of this in the context of this study is surmised:

- “The purpose of evaluative research is to find out how well something works”

- [Evaluative studies assess] "…not only 'how effective' something is, but also 'why', and then comparing this explanation to existing theory"

Both from (Page 176, Saunders et al., 2015).

Conversely, descriptive and explanative studies are discussed to work in tandem to provide analysis of exact events which have taken place (Saunders et al., 2019) and the significance of these. It has been outlined how combined studies are prevalent in research (Saunders et al., 2019), therefore it is reasonable to suggest that descriptive and explanative aspects are also evident in this study. It is acknowledged that a description (Lucienne T M Blessing & Chakrabarti, 1995) of existing processes should take place prior to prescription of solutions. Description is achieved through extensive literature review conducted on the guidance of key literature on the subject (Chris Hart, 2009).

1.6.2. Case Study Approach Justification

Pragmatism typically produces in-situ outputs of real world value (Elkjaer & Simpson, 2011), so the researcher being a part of the work is necessary. As pragmatism seeks to answer "how" or "why" questions with exploratory themes, a case study approach is considered to facilitate this (Robert K. Yin, 2014) better than other methods considered, though action research has also been observed to bear similarities (Kumar, 2014) to what is sought to be assessed in this work.

Action research has been discussed to follow "advancement of practice" (Page 127, Kumar, 2014) (Carr & Kemmis, 1986). As such, many of the key tenets of action research are of interest to this study, but many elements also contrast with the requirements of this work. Action research is discussed to seek "involvement of community members" (Page 127, Kumar, 2014) using a "collaborative approach" (Page 202, Saunders et al., 2019), which is not sought from this work. It has been discussed how "people have the right to contribute to decisions which affect them" (Page 189, Reason, 2006); however, this is of greater concern when implementing into organisations, whereas this work seeks to learn about the process at a level prior to that step. It is sought to ensure that the contribution proposed in this thesis is **technically capable of delivering solutions** before exploring the inputs from the community and the usability; it is, however, acknowledged that this is an important *next step*. This suggests action research may be of utility in future studies. Action research is noted to be strongly espoused (L. T. M. Blessing et al., 1998) (Lucienne T M Blessing & Chakrabarti, 1995) in design research; however, with user inputs advocated here. As intimated, this study seeks to assess whether the proposed solution is capable of delivering solutions at all before applying comparative action research (L. T. M. Blessing et al., 1998) to determine the exact nature of effects. If the solution developed is not capable of producing functional solutions, there is not use in exploring its use to the community.

Outcomes in action research which surround “addressing worthwhile practical purposes” (Page 188, Reason 2006) *are* of interest to this work, but this is something also considered to be facilitated by case study research. Indeed, it has previously been commented that if either the participation or action element are missing the research cannot be considered to be action research (Greenwood & Levin, 2007). Seminal works on design research methodologies clearly outline use of case studies as a means to evaluate developed methods: Duffy (1998) specified case study as a valid means of evaluation, whilst “diary keeping” (L. T. M. Blessing et al., 1998) has also been outlined as a valid means of data capture. Blessing (1998) has also drawn attention to instances where non-comparative observation has been used for data capture. This study has not had the resource to train an expert engineer in the use of the solution develop and then observe them using it, therefore case study has been used to capture this information; i.e. the research *is* the expert in using this solution and has documented as necessary. This allows assertion that this work is not action research.

Case studies allow the effectiveness of the work to be tested empirically *by the researcher* in a real setting (Robert K. Yin, 2014) (Lucienne T M Blessing & Chakrabarti, 2009). As such, the work can be approached such that “thorough, holistic, and in-depth exploration” (Page 123, Kumar, 2014) and understanding can be realised in a real-life setting (Robert K. Yin, 2014). This work seeks to evaluate steps taken and outcomes produced by applying the solution developed, something other authors have noted as a strength of case study research:

> “The essence of a case study, the central tendency among all types of case study, is that it tries to illuminate a decision or set of decisions: why they were taken, how they were implemented, and with what result.” (Schramm, 1971)

This synopsis – along with others alluded to already - of case study research closely aligns with the requirements of this work. It is sought to understand the effectiveness (“with what result”), and how and why it is or is not effective. It is described how case studies can be applied to typical cases (Kumar, 2014) in order to develop a thorough understanding of the dynamics and function of a key metric within that application case (Robert K. Yin, 2014). This is what is sought: to apply the solution in typical instances in order to understand and “extensively explore” (Page 123, Kumar, 2014) its idiosyncrasies (Burns, 2000) in relation to its probable use cases (Saunders et al., 2019).

It is well-documented how a case study is likely to require various methods to capture information of interest (Saunders et al., 2019) (Robert K. Yin, 2014). Each case study attempts to progress in difficulty and consider new aspects during application of the developed solution. A multiple case study approach is taken in order to assess whether literal replication (Robert K. Yin, 2014) can be achieved in terms of effective solutions being developed, though it is considered that the cases covered in this thesis have been specifically selected such that analysis of "a phenomenon few have encountered before" (Page 198, Saunders et al., 2019) can also take place to develop an understanding of "…the case in its totality" (Page 123, Kumar, 2014).

The use of multiple cases is considered to facilitate answering the general question of whether the solution is capable of producing functional solutions, whilst specific application in each case study is designed to provide the depth of detail required to understand how it works and how effective it is from task to task. The specifics of each study are summarised, as follows.

Table 1: Overview of the assessment undertaken throughout thesis.

Assessment	Assessment Criteria	Description
Case Study 1	Qualitative and Quantitative	• Assessment of applying the solution to component selection for the redesign of actuation solutions in an existing robot arm; • Simulation of the actuation package developed by this approach to component selection; • Installation and physical testing of the actuation package developed by this approach to component selection; • Comparison of the simulation and physical testing results; and, • Comparison of performance, cost, mass, etc. of the old design versus the new design, and breakdown of effects of the component selection approach selected.
Case Study 2	Qualitative and Quantitative	• Using the solution to develop a new actuator; • Utilising the solution alongside an overarching engineering design methodology; and, • Simulation of the new actuator to gain simulated results of its performance.
Case Study 3	Qualitative and Quantitative	• Use of the solution in delivering a solution for industry; and, • Simulated and physical testing of the design, ensuring that the solutions yielded by the solution are viable and effective.

In the studies mentioned in table 1, thorough evaluation will take place by means of applying the solution developed across the studies. Capturing data from a variety of sources in these processes will allow evaluation of the in-situ application of the solution. Validation of the outputs of this process will take place primarily via simulated and physical testing of the results produced by applying the solution, though cross-reference with other literature may also assist in validating aspects. Verification will be achieved by comparison to established works which ratify the claims of this work. Verification is also deemed to be achieved by conducting a number of studies and ensuring that each corroborates the other and by means of conducting several studies in order to ensure that the results corroborate one another.

The initial tasks of the research process are illustrated in figure 3, breaking down how the tasks are considered to relate to one another. Solution and Evaluation are highlighted in blue, as they are dealt with specifically elsewhere. Chapter 3 covers the solution developed, whilst table 1 has already broken down the elements which feed into the case study-based evaluation process.

Figure 3 illustrates the approach taken to evaluate the developed contribution. With reference to key methodologies in engineering design, shown in figure 4, on the following page, it can be seen the approach taken can be considered to be corroborated by these approaches. Description 1 is achieved through literature review, whist this same literature review informs the research problem (design problem, hypothesis, solution, etc., as per Duffy (1998)) and distillation of information from this phase enables "prescription" of a solution. Evaluation is then enabled by prescription of a developed solution, which through evaluation facilitates "description II". Application of the solution in a design practice-informed evaluation process (Duffy & Donnell, 1998) then enables documentation of the outcomes, where 2a and 2b of (Lucienne T M Blessing & Chakrabarti, 1995) explore the effects of applying the prescribed solution relative to the initial problem and existing literature, which is covered extensively throughout chapters 5 and 6.

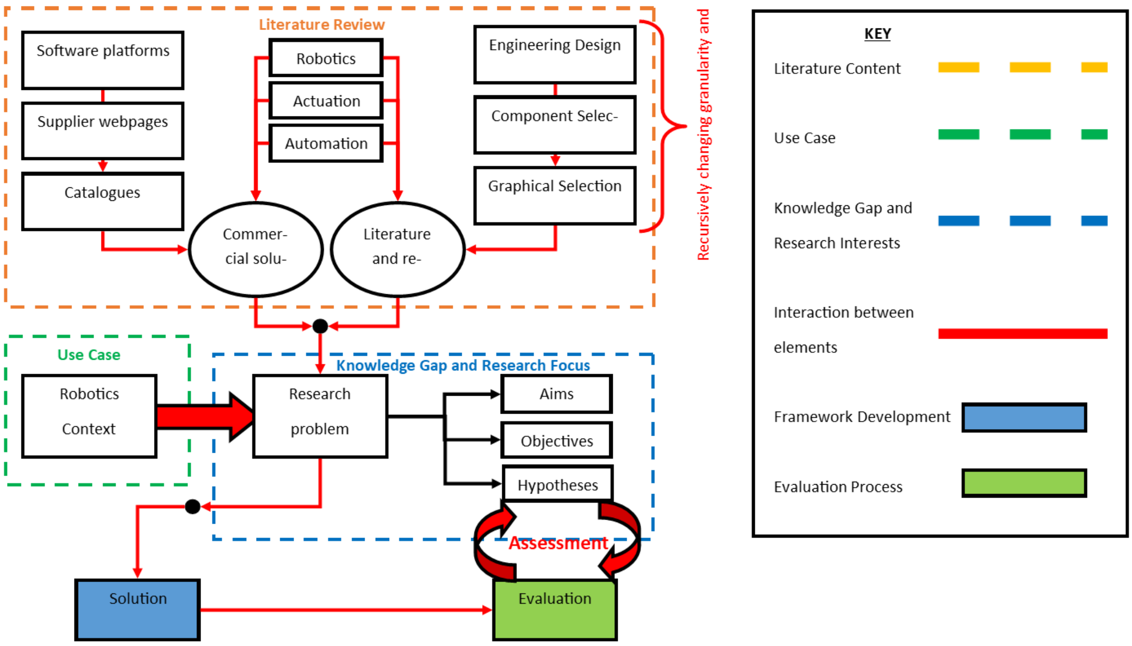

Figure 3: Model of processes, highlighting the "front end" of research; i.e. definition of task, etc. These tasks are supported by the methodology outlined in this chapter.

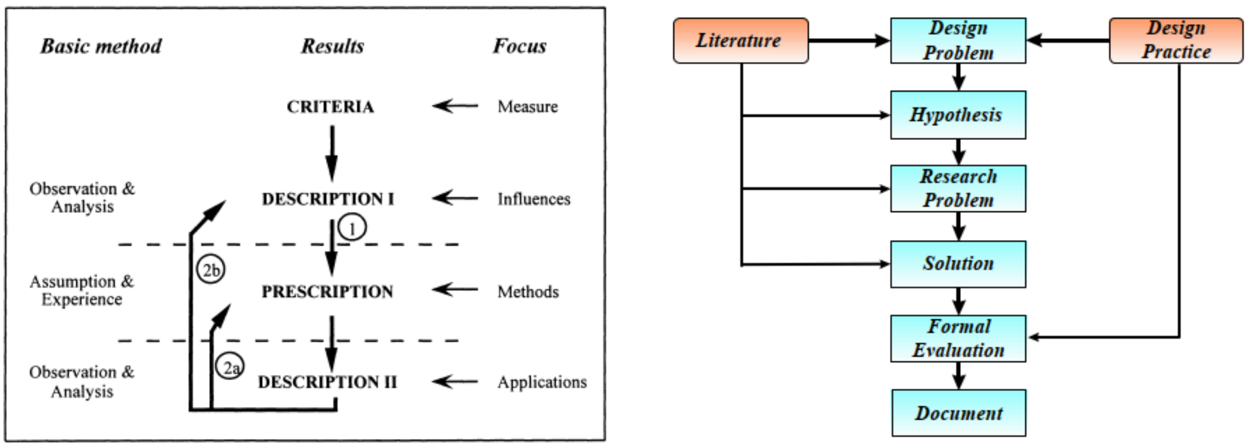

Figure 4: Research methodology overview as per Blessing (1995), left. Research methodology as per Duffy (1998), right.

2.0. Literature Review of Component Selection Tools and Methods in Mechatronic Design

In the context of component selection in mechatronic engineering, it is important that mechatronics design is first understood, and, in particular, how the component selection task is already supported within existing mechatronics methodologies. It has already been discussed in the previous chapter how a robot can be considered a "narrow subset" of mechatronics devices, therefore its actuators can be considered as an even narrower subset of mechatronics.

2.1. Mechatronic Systems Design Methodologies;

Seminal texts outline heavily utilised approaches and outline the complexity of mechatronic design (Gausemeier & Moehringer, 2002b). In support of mitigating issues encountered in the development of such complex systems, a variety of models, frameworks, and methodologies have previously been employed. Some of the most prominent instances encountered are discussed herein.

2.1.1. The V-Model

The V-model is one of the most core models used to assist in aiding mechatronics design challenges. Despite originally being published for software applications (Brohl, 1995), it is noted to be "one of the most important models for the development of technical systems" (I. Graessler et al., 2018). Resultantly, the VDI 2206 guideline (Gausemeier & Moehringer, 2002b) established a comprehensive model for completing mechatronic systems engineering projects (figure 5) and subsequently, various interpretations of this V-model have been applied in the subsequent years, with their differences delineated in recent publication (I. Graessler et al., 2018), as illustrated in figure 6. New and updated V-models have also been proposed to include technical and social developments (Iris Graessler & Hentze, 2020) since the publication of the initial guideline; see figure 7.

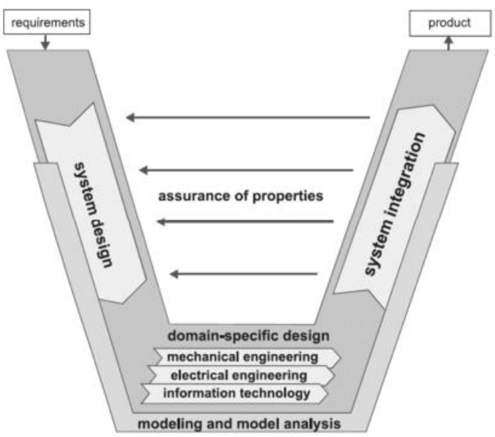

Figure 5: V-Model from VDI 2206:2004. "Design methodology for mechatronic systems".

#	Characteristic properties	VDI 2206: 2004	US DoT	Binz, Watty	Eigner, Gilz, Zafirov	Bender	INCOSE SE4.0
1	**Decomposition into System levels**	Not illustrated	Yes, by wording	Not illustrated	Not illustrated	Yes, three levels	Yes, three levels
2	**Integration of model-based development approach**	Yes, partly	No	Yes, partly	Yes, plus virtual tests	No	No
3	**Provide status revision**	No	Yes, decision gates	No	No	No	Not illustrated
4	**Life cycle representation**	No	Yes	Yes	Yes, backbone	No	No
5	**Focused fields of application**	Mechatronic systems	Infra-structure systems	Micro-systems tech-nologies	Model-based Systems Engineering (MBSE)	Embedded Systems	Systems Engineering
6	**Sequential or iterative approach**	Hints for iterations	Sequential, straight forward process	Iterative	Iterative	Iterative	Sequential, straight forward process
7	**Adaptability to maturity levels**	Yes	No, just for large and complex infrastructure projects	Yes	Yes	Yes	Yes
8	**Tutorial quality**	Wording partly unclear	Many sequential steps are easy to follow	Procedia and wording partly unclear	Procedia partly unclear	Procedia partly unclear	General explanation is easy to follow
9	**Adaptability for domains**	Yes, very generic	No special focus	Yes, very generic	Yes	No, explicit description	Yes, very generic
10	**Consideration of Requirements Engineering**	Described as an input	Partly for definition	Described as an input	Described as first level of development (RFLP)	Partly for definition	No, schematic model
11	**Verification and validation**	Right to left	Left to right	Right to left	Right to left	Left to right	Left to right

Figure 6: Comparison of various V-models – (I. Graessler et al., 2018)

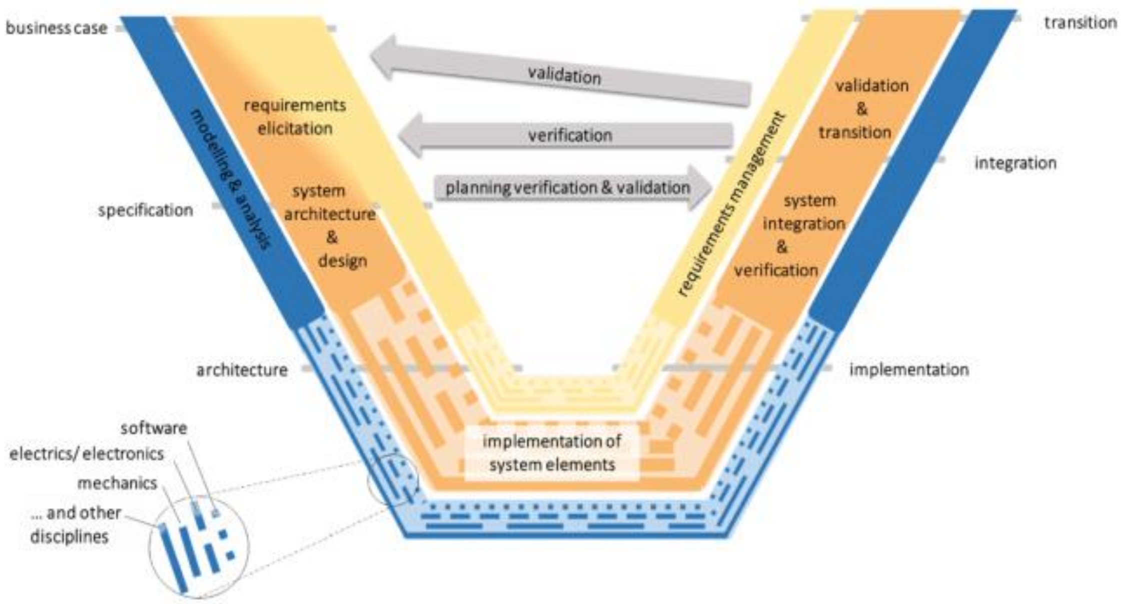

Figure 7: The New V-Model.

Figures 5 and 7 are considered to demonstrate evolution of the V-model, whilst figure 6 helps to draw attention to some of the nuanced differences between iterations of these distinct model variants. Of particular interest, row 8 of figure 6 draws attention to the difficulty in following these processes due to issues with clarity. Coupled with the vague reference to component selection, this cumulatively suggests merit in exploration of whether clearer and more specified guidance can be offered to support component selection from other methodologies.

Further instances of the V-model have been interrogated for specific applications (see appendix A.1.), such as: D'Assault Systems RFLP-augmented V-model (Mlambo et al., 2018) and frameworks where the V-model is used as a means increase interdisciplinary design (Kernschmidt et al., 2018). Others are also encountered. Crucially in the context of this work, many refer to the component selection task in some form, whilst extremely limited discourse on *implementing* this task is offered. This is something noted across engineering design methodologies, not only those targeted towards mechatronic design (Gerhard Pahl et al., 2006) (S. Pugh, 1990). Acknowledgement of the task is significance, as it demonstrates that it is a key task in the overall process; however, as stated, no specific guidance is provided to aid this process despite its acknowledgement. Throughout mechatronic design literature, component selection is noted as a key activity, but no support in this activity is enabled through use of the V-Model in any of its incarnations.

2.1.2. Other Mechatronics Methodologies

2.1.2.1. Methodology for Reliability Prediction of Mechatronic Systems

The methodology for quantification of reliability in design of mechatronic systems is found to be one of the more thorough methodologies encountered in literature. Broadly, it follows many of the overall high-level steps that the V-model does, but there are particular elements of the methodology which are of significance to the component selection task.

With reference to figure 8, step 8 is noted to be of particular relevance, names "components data gathering and processing", this is loosely construed as component selection:

> "The objective of this step of the methodology is to identify the distributions of reliability (lifetime distributions) associated with the components and then gather, and process the data in order to calculate their parameters values" (Page 243, Habchi & Barthod, 2016).

The emphasis of this methodology is on the context of reliability; however, this statement is inferred to require that suitable components are first interrogated before their reliability and other parameters can be assessed, which requires a selection process. The argument can be made that without an effective support to assist this selection activity, the subsequent assessment of reliability can be negatively affected. The methodology itself does not propose any techniques to support this activity, therefore the user is left to find another approach or adopt an ad hoc approach to the task, as is often the case.

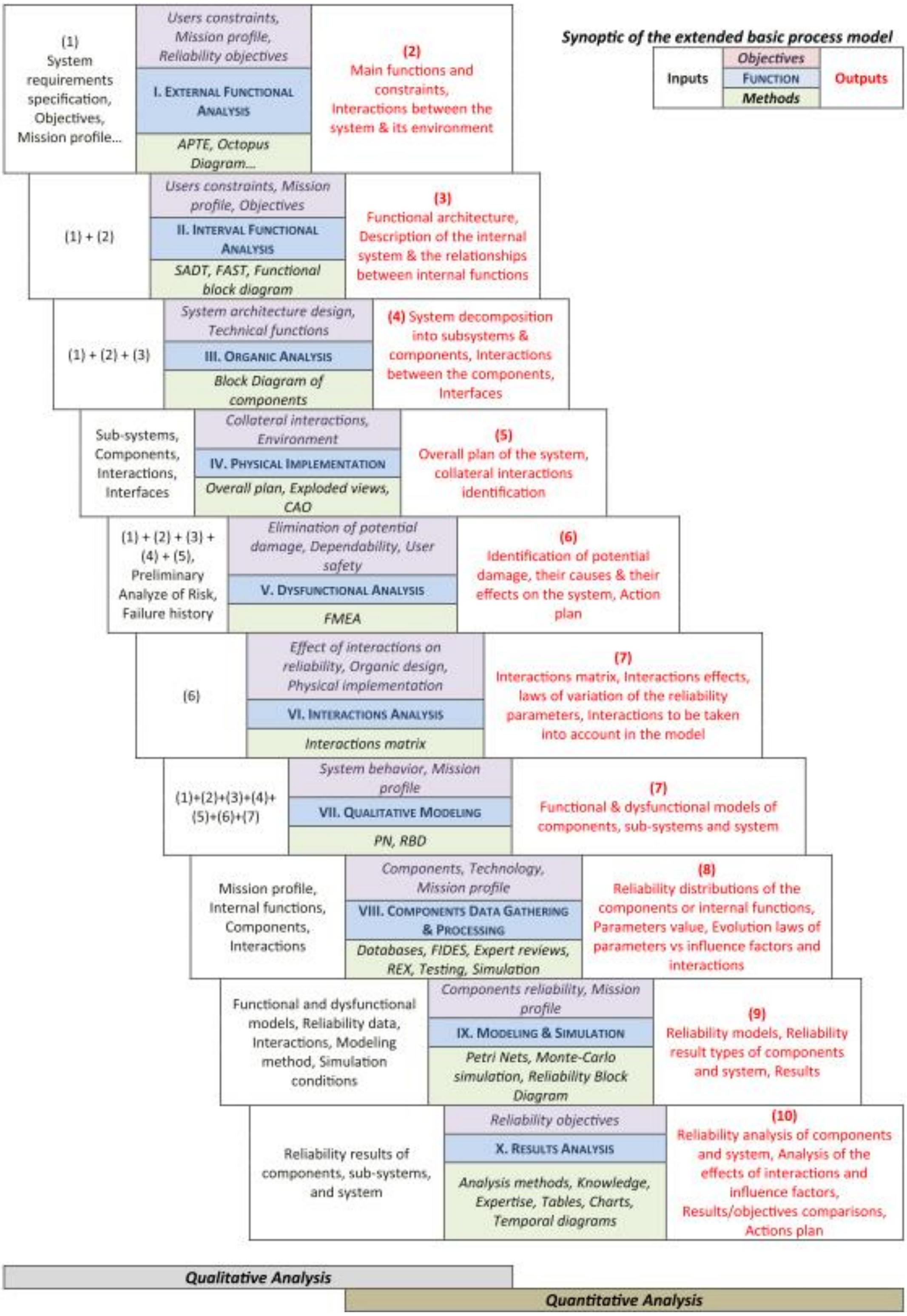

Figure 8: Habchi's 10-step methodology for "analysis and quantification of reliability during the design phase of a mechatronic system" (Habchi & Barthod, 2016).

The inclusion of the qualitative and quantitative spectrum at the base of the methodology is also considered to be a critical insight, especially when considered in the context of existing approaches. From experience, it is noted that many selection strategies mention and support review of *quantitative* information, with little allusion to the significance of qualitative information on the capability of a component to fulfil a given requirement. Habchi has astutely noted that much of the component selection exercise owes a great deal to consideration of qualitative information *as well as* quantitative parameters, as per figure 8.

2.1.2.2. The Mechatronic Design Process Model

Shown in figure 9 is the Mechatronic Design Process Model, as suggested by (Zante & Yan, 2010). It is noted to support a development based on French's model, with enhancements included which rely upon concurrent engineering and mechatronic life-cycle principles being embedded into the model.

The Mechatronic Design Process Model is noted to acknowledge the correct information in terms of component selection. Note that component matching and sizing is specified as a specific task to be encountered and completed, whilst the database to be relied upon is also noted to be a significant contributory factor. The further ratifies the significance of this activity in mechatronic design.

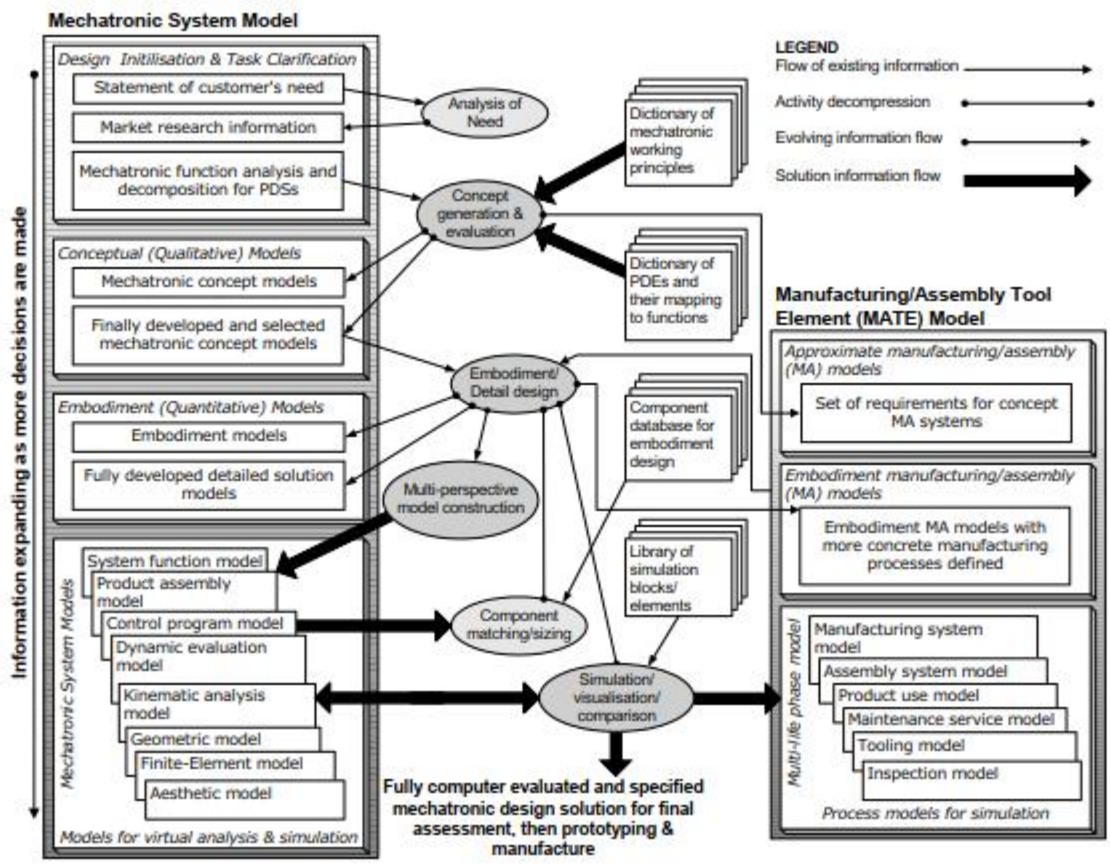

Figure 9: Zante's Mechatronics Design Process Model.

As noted during discussion of the V-Model, the guidance to support the task of component selection in this mechatronics design model is also found to be quite limited. Again, the user is provided with guidance as to the point in the design process to consider this activity; however, no guidance is offered to support implementing this task. The use of component databases are referred to, but strategies to support selection or to interrogate information are not included in any further discussion.

With reference to figure 9's legend, it can be seen that the "component matching/sizing" activity is subject to "activity decompression", as defined by the authors of this article. In the article, this idea is not found to have been expanded upon beyond its mention in this figure's legend, requiring some inference from the reader. The task is inferred to involve moving this task to another stage in the design process. Presumably, this is considered to enable the user to focus more clearly on other tasks in the embodiment design activity. A question arises regarding whether migration of this activity might impede effective completion of this activity. With the embodiment design changes, the criteria and considerations for component selection may also evolve. Furthermore, without a clear understanding of component performance *available* it is conceivable that by addressing this selection activity late in the design phase, issues may be encountered in even realising the solution as a result of absence of suitable components.

Lack of consideration of these aspects may overlook issues pertaining to component selection's relationship with other elements of the design task or with other components to be selected. Such an issue may introduce need to consider the effects of changes in design at latter stages and the issues involved in this (Siddiqi et al., 2011).

2.1.2.3. TiV Model

A similar approach is noted to have been recommended in the TiV Model (Melville, 2014). Again, system models are discussed as a means to support the way in which mechatronic design tasks are approached, with specific reference to the types of task which are included at each stage.

It is discussed how component design should be considered in the "evaluative" stage of the mechatronic design process, whilst the "productive" stage is shown to be where component databases are interrogated. As in previously discussed works, the necessity to consider component selection as a discrete task is clear; however, specific guidance on the interrogation of information to enable successful completion of this task is not included.

It should also be noted, as per figure 10, that the component database interrogation task is only considered at the production level. Something similar is proposed by Zante (2010). As argued in response to Zante's model, it suggested that the consideration at this stage neglects the opportunity to be responsive and amend the design with respect to findings from the component selection tasks alongside the overall design task; if the right component is not available late in the design process, compromises will have to be made. Doing so later in the task introduces risk and will necessitate a greater array of changes being made, which may become more difficult to amend at this point in the task as it is well-documented how changes later in the design phase can be costly (Siddiqi et al., 2011).

Unlike many of the other methodologies covered thus far, Melville's stance to consider COTS components at the "quantitative" stage is positive. Highlight of this specifically raises consideration earlier in the design phase, allowing it to be ensured that consideration of available components are considered earlier than the production stage. This is not communicated in the overall TiV model in figure 10, but in a separate definitions illustration, as referenced in figure 11.

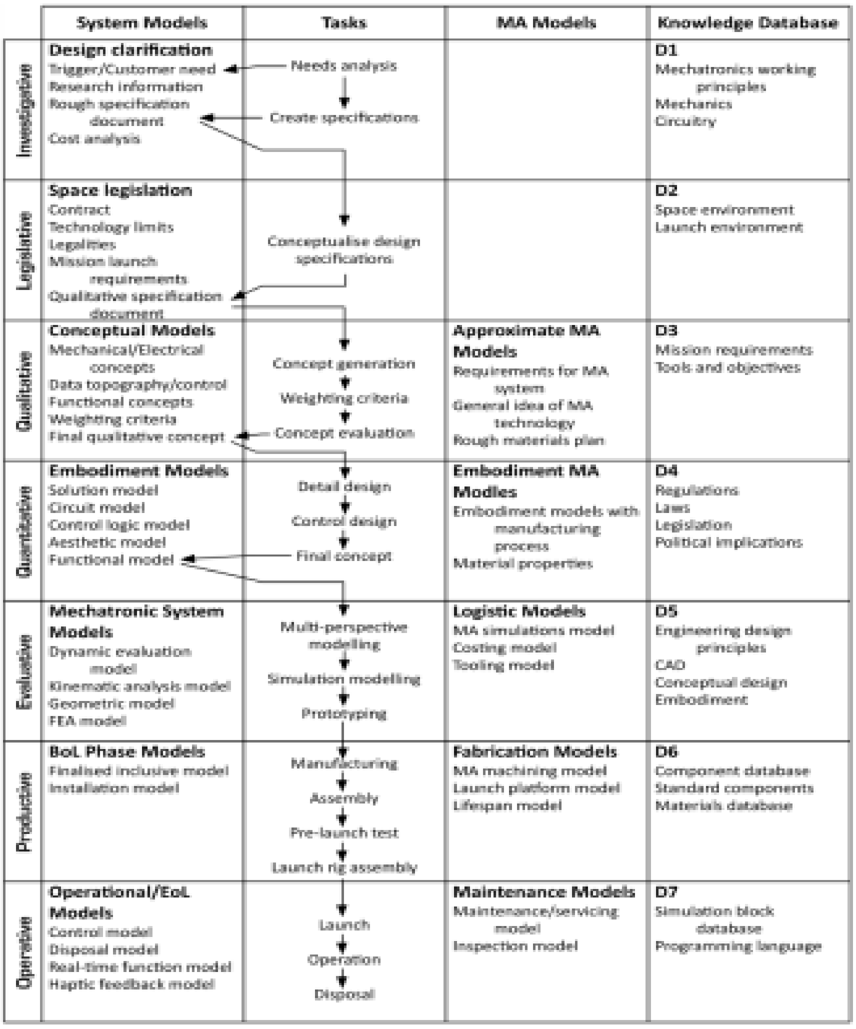

Figure 10: TiV Model (Melville, 2014).

Stage	Description
Investigative	User needs, market research, technology research, specification generation
Legislative	Planning, mission statement finalisation, contract agreement, qualitative spec. document
Qualitative	Initial design proposals, mechanical/electrical/control concepts, general solution proposals, ballpark costing
Quantitative	COTS component specifications, detailed design, subsystem design, costing, custom part design, data scanning for 3-D reconstruction of manufactured parts
Evaluative	Prototyping, simulation of launch, system performance and manufacturing facility, final solution decisions, meshing and model reconstruction based on scanned data,
Productive	Part creation/buy-in, subsystem assembly and testing, system assembly and testing, system modifications and tweet based on reconstructed models from scanned data
Operative	Launch, operation, control, maintenance, repair based on 3-D scanned data, inspection, and disposal

Figure 11: Definitions from TiV model phases. *Highlight added.*

2.1.2.4. Hierarchical Model

A hierarchical methodology for undertaking mechatronics design tasks is also noted to be proposed in literature, as illustrated in figure 12, below.

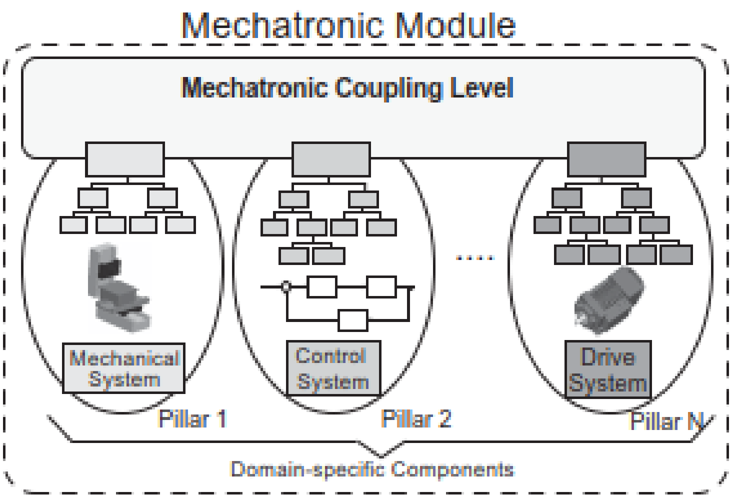

Figure 12: Hehenberger - hierarchical approach.

As with other discussed works, credence is again given to the need for selection of standard components in this paper:

> "The process of defining hierarchical levels must be repeated until elementary FRs [*functional requirements*] (e.g. proven solutions, standard components) with their associated, well known DPs [*design parameters*] are achieved." *Italics* *__added__ for clarification.* (P. Hehenberger et al., 2010)

Specific guidance on approaching interrogation of qualitative and quantitative information surrounding component performance is again not supplied, and guidance on decision-making to aid completion of this process is also notabley absent.

2.1.2.5. Others

As with many other instances discussed in this section, other methodologies for completing mechatronics design tasks have been encountered which acknowledge the importance of the task of selecting components without providing specific instruction as to how best to approach such tasks. Other instances include proposed systematic guideline steps (Salem, 2014), step-wise guidance which augments the V-model (Vasić & Lazarević, 2008), and multidisciplinary interface models (Zheng et al., 2017), figure 13, which are seen to refer to component selection in guiding the overall mechatronic design process, but without specific allusion to how particular aspects of such a task should be undertaken.

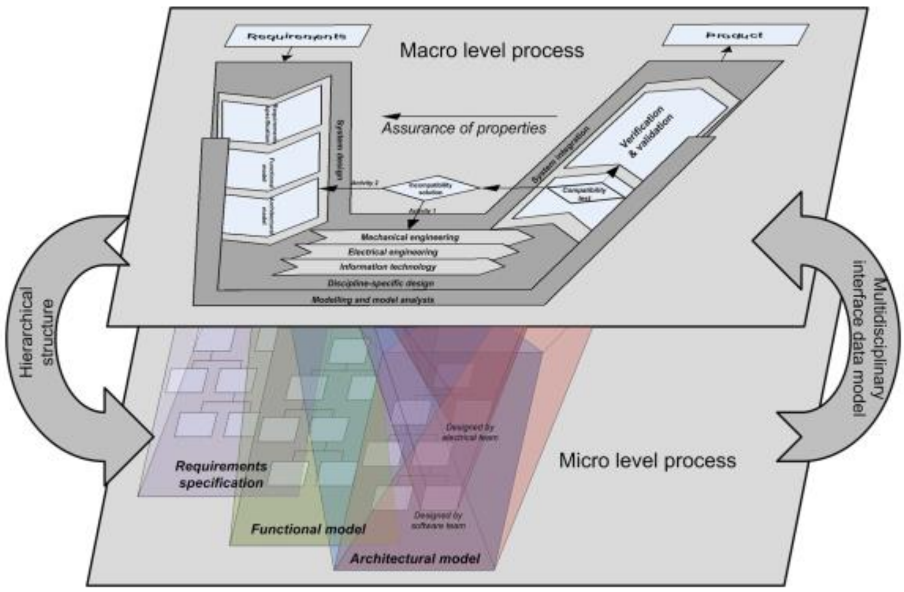

Figure 13: Hierarchical and V-model hybrid methodology (Zheng et al., 2017).

Some niche design strategies have been encountered for design of very particular systems (Cianchetti et al., 2009), with evidence of their application (Laschi et al., 2009). As in other instances covered in this section, specific guidance on selection of components is not supplied, but the significance of the process is noted. Others robotic and machine design methodologies have been encountered, including user-centred approaches specific to design for human-machine interaction (Coelho et al., 2008), found to be lacking in technical definition for approaching tasks. Other methods encountered also tended to focus on collaboration (Mcharek et al., 2019), simulation-based mechatronic design (Dohr & Vielhaber, 2014), or process optimisation (Marconnet et al., 2017) augmenting the V-model.

2.1.3. Summary of Models, Methodologies, and Frameworks to Support Mechatronic Design

Thematically within the context of this thesis, all of the methodologies, models and frameworks discussed previously are found to have very similar issues: they are virtually all found to mention specifically the need to complete the component selection task and highlight that databases should be interrogated in doing so; however, no specific guidance to support selection, the type of information to be sought, or methods leveraged to interrogate databases are proposed or alluded to.

Fundamentally, these methodologies deal with specific problems in mechatronic design but tend to do so at a higher level of granularity than the solution proposed would seek to achieve. Mechatronics design methodologies are found to operate at a level which supports the overall process of design from start to finish, commencing with market inputs to develop a specification and ending with delivery of a finished product or system. The solution proposed would facilitate guidance through the particular task of selecting components, which is quite idiosyncratic in the scheme of mechatronics design overall.

The methodologies already reviewed are found to acknowledge the significance of component selection, but do not support the activity well. It is therefore required that existence and applicability of approaches specific to component selection are also reviewed, to develop clear understanding of existing approaches.

2.2. Selection and Decision-making in Engineering Design

Clear understanding of the activities undertaken in selection should be considered as part of development of a selection solution. A significant body of seminal work in this areas has previously been published, which has allowed clear understanding to be developed.

Engineering design tasks are undertaken by engineering designers (Gerhard Pahl et al., 2006). The design task can be undertaken by various types of engineers; a mechanical engineer designing a mechanical system is still an engineer conducting a design activity. In these applications, engineering designers (regardless of their discipline) are noted to be interested in "what it does" information on components, with little regard for how the component functions (Harmer et al., 1998).

There is consensus surrounding some of the critical steps to take in a selection activity. There are several works citing reliance on a design specification as a critical starting point (Hughes, 2013b) (Egbuna & Basson, 2009), enabling translation of this information into functions required of the system being developed and attributes required of solutions (Harmer et al., 1998). Others support a similar approach, though in a more case specific manner (Weaver & Ashby, 1996), though the intent to define objectives and parameters to be met is still clearly evident. This starting point is supported in well-established selection processes from other fields, including materials selection (Ashby, 2005) and selection of manufacturing processes (Shercli & Lovatt, 2001).

After this initial definition of requirements, it is argued that "successful selection of engineering entities involves two main steps: screening and supporting information" (Cebon & Ashby, 1997); this is illustrated in figure 14. Within these two main steps, there exists a sequential operation of interrogating information, making comparisons, and a selection decision being made. Fundamentally, as described by Cebon, the screening process facilitates reduction of the range of items under consideration, whilst the "supporting information" step supports further interrogation of *specific* information such than an individual instance can be selected; i.e. a specific material grade or a specific motor model. Further, it is asserted that "the screening and supporting information steps are characteristic of all engineering selection activities" (Cebon & Ashby, 1997). The subsequent success of future work (Ashby, 2005) and associated commercial solutions (Granta Selector) suggest that this characterisation is likely an accurate one. It is outlined that selection strategies and methods for searching differ depending on the specific nature of the task (Cebon & Ashby, 1997), something which is corroborated throughout literature (Ashby, 2005). Some mechatronics methodologies do acknowledge the significance of "supporting information" (such as "manufacturers' databases" (Zante & Yan, 2010) (Melville, 2014)), but their relevance to the screening process and supporting through this process is not acknowledged. As argued in section 2.1.3., this suggests that the significance of the task is noted, but the complexity and nuanced aspects of the task are poorly understood.

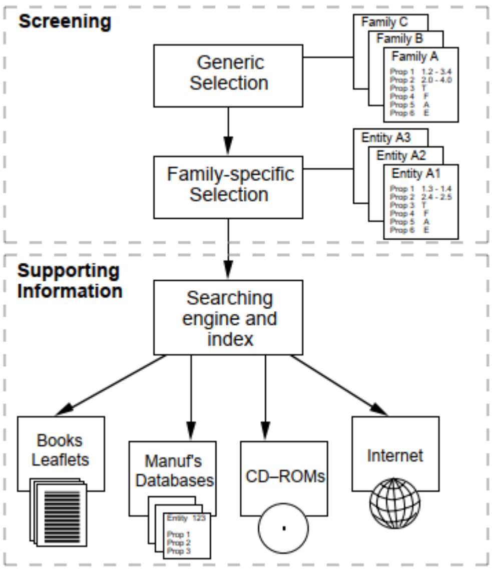

Figure 14: Two main steps of a selection activity (Cebon & Ashby, 1997).

The specifics of these two tasks are further expanded upon by Cebon; however, other literature which deals with exact challenges at this stage in a selection process have not been able to be located during review. During the screening process, databases are remarked to require interrogation, but for the task to be effective these databases must be *comprehensive*, *complete*, and *universal*; succinctly, “Screening is performed by linking the technical and economic requirements of the design with the attribute profiles stored in the screening database(s)” (Cebon & Ashby, 1997). Completion of the screening phase, should provide engineers with an output of shortlist of candidate solutions, which is ripe for interrogation of “supporting information” necessary to make an informed decision as to a specific instance which should be utilised. Cebon and Ashby’s paper culminates with a clear assertion of what is required of databases interrogated for the purpose of enabling any selection activity. This is illustrated in figure 15. This gives overview of the information required to interrogate in selection and the steps which support interrogation; however, it is important to also consider how choices are made upon interrogation of this information. This is something which has been noticed to be less specifically guided in academic literature.

(i) A database suitable for *screening* should have the following characteristics:

- It should be *comprehensive* – contain all general classes of entities in the 'kingdom' of interest.
- The attributes it contains should be *universal* – common to all of the entities in the database. The attributes should further satisfy the requirements of *comparability*, *measurability* and *discrimination*.
- It should be *complete* – have no holes or gaps without any data. This can be achieved by the use of *approximations* and *estimates* to fill the holes.
- It should have a *relational* structure (or similar), to minimise data redundancy.
- It should, where possible, exploit a *hierarchical* taxonomy, so as to facilitate data checking between layers of the structure.
- Range checks and physically-based relationships between the attributes should be used to implement automatic data checking procedures.

(ii) The *supporting information* system can have information stored in any format. The only requirement is that items of information should be 'tagged' according to the identifiers of records in the screening database. Once a particular entity has been isolated by the screening process, all information about it can be retrieved rapidly from the supporting information system.

Figure 15: Conclusions of Cebon and Ashby (1997) on requirements of information interrogated during selection activities.

In light of the discussion from the last two paragraphs, there is a need to make a distinction between decision-making and selection of any type. As already discussed, the selection activity is noted to comprise of phases, where definition of requirements particular to the selection task is undertaken, followed by “screening” and “supporting information” phases (Cebon & Ashby, 1997). It is considered that these phases constitute what is involved in *selection*. Decision-making is observed to be an action which takes place – often many, many times – *during* selection, with selection comprised of two “phases”. From review, it is understood that decision-making in selection tasks is widely accomplished by providing the engineer with all the relevant information, and then by allowing them to use their expertise and training to *make* the decision.

Selection activities in engineering design are evident throughout any project, from definition of a methodology to guide the activity through to selection of concept-generation techniques, selection of a best solution, selection of materials, etc. In component selection, and with reference to the V-model, provided below in figure 16 (Kernschmidt et al., 2018), it can be seen that standardised component selection is considered to be undertaken around the nadir of the overall mechatronic design process, where the input requirements from standardised components are specifically highlighted. This task being undertaken at this stage is corroborated across various iterations of the V-model, and at similar stages across other mechatronics design methodologies, as discussed earlier in section 2.1.

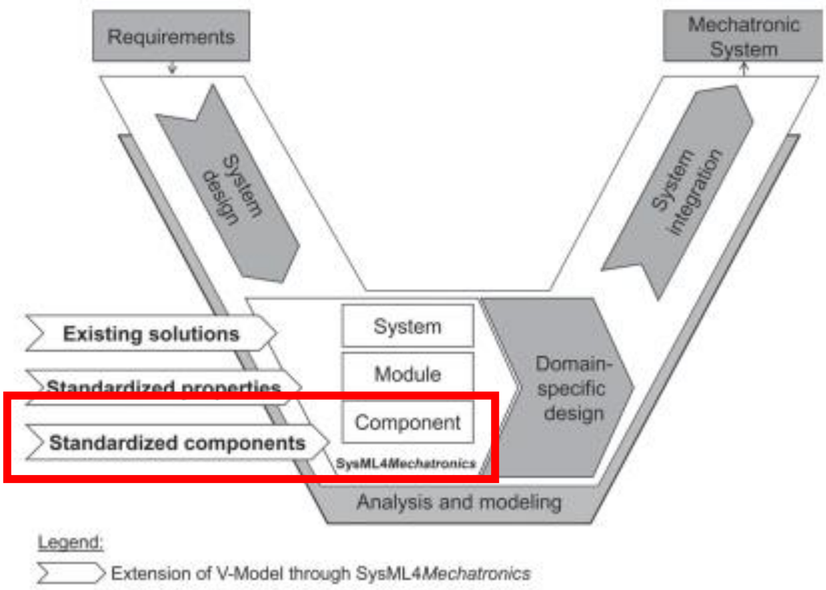

Figure 16: V-model from Kernschmidt (2018).

The particular significance of component selection tasks with respect to *where* in the design task they take place is also addressed in engineering design methodologies. Pahl and Beitz (2007) outline how in concept and embodiment-level tasks there are specific steps of which selection activities (such as component selection) can be considered critical elements. An observation made by this researcher is that, in line with Pahl and Beitz’s view, selection tasks of this nature are not the milestones they are represented as in many instances from section 2.1. Selection tasks evolve with the system’s design changes, and most selection tasks, be it for materials, a manufacturing process, or components, should be considered concurrently with other design tasks undertaken throughout the process.

Selection and decision-making are commonly encountered in any engineering design activity or project. Design of new systems is a process which is paved with the need to make many choices at varying levels of granularity. In turn, each of these decisions comes with a consequence, where even seemingly small decisions can have large impacts on performance, monetarily (Siddiqi et al., 2011) and in project delivery times.

2.3. Review Focus

This primary interest of this thesis is component selection in the development of mechatronic actuators to be used in robot arms. So far, review has been taking place to ascertain the significance of component selection in mechatronic design and to establish a fundamental understanding of what is meant by component selection and what the activity is comprised of. In order that detailed information can be captured to support proposition of a novel solution further review must take place to capture particular information which is considered most likely to be relevant to this solution.

Targeting the areas of literature of greatest significance to this exercise has been achieved by relying on the findings of exploratory review conducted in sections 2.1. and 2.2. Almost all literature endorse a step-wise approach to mechatronic design, where component selection (or related actions) are noted to be significant tasks. A focused literature review is therefore required to develop a deeper understanding of the *specific* relevant literature, such that clear needs and opportunities are able to be clarified. This also facilitates comparison of the solution proposed with existing solutions.

On the subject of taxonomy, 2 publications within the engineering design context endorse the need for clarification of categorisations as a means to understand technical systems (Gerhard Pahl et al., 2006) (Hubka, 1988), whilst an important paper on the topic of selection cites taxonomy as being crucial to the selection activity (Cebon & Ashby, 1997). It is therefore critical than some exploration of this topic takes place in more detail. The need to interrogate or utilise quantitative information is specifically noted (Habchi & Barthod, 2016), whilst review of qualitative information in selection is note noted to be reviewed. There is, therefore, value in further exploration of both these topics.

In review of some mechatronics design methodologies (Melville et al., 2015) (Zante & Yan, 2010), an issue was highlighted about potentially anachronistically approaching the selection task. This raised questions about the component selection activity as it relates to the overall system design, and as to how one component being selected affects others being selected. Since many of the components in a system such as an actuator are linked in many ways, it is considered necessary that some review of whether the significance of these relationships in the physical system has been assessed before, particularly in the context of how selection of *a* component can affect others.

During analysis of what is involved in the selection activity, it has been noted that selection tends to take place without use of formalised methods for decision-making, such as weighted methods, etc. From experience, these are known to be effective in selection in other areas of engineering design, so it was decided that further review in this area would be a worthwhile endeavour. Since this work is focusing on design of actuators through enabling component selection, it is considered somewhat axiomatic that review of the above topics should take place in the context of actuator design and/or component selection.

2.3.1. Summary of Research Focus

From review of relevant literature consulted in early stages of the project, a clear focus has been attained in terms of where the remainder of the review efforts should be targeted. This has been based on themes identified from initial exploratory literature review, as covered in sections 2.1. and 2.2., whilst the recommendations from figure 15 have also clarified the need to provide a strong database and means to interrogating this information. The remainder of review will focus on the following key areas:

- Existing formal processes (methodologies, frameworks, strategies, process flows, etc.) used to guide the process of completing a component selection task;
- Review of existing formal processes (methodologies, frameworks, strategies, process flows, etc.) used to guide the process of actuator design;
- Taxonomy and categorisation of component and actuator information, particularly that which is pertinent to the scope of this research;
- Review of how quantitative and qualitative information is currently interrogated by engineers;
- Component selection's effect on system design and on the selection of other components; and,
- Review of whether formalised decision-making processes are leveraged in the process of component selection to assist engineers in making decisions.

Figure 17 illustrates how these focus points have been arrived at by cross-referencing their overlap with key literature covered in section 2.1. and 2.2. This figure illustrates the themes which have emerged as 6 column headings, and clarifies how key texts overlap with these themes. Strong relationships is where literature directly suggests the need to consider the column heading in the context of component selection or selection in a more general sense, moderate relationships suggest utility or have applied content from the relevant heading in another field/application, whilst weak relationships mention content relevant to the column heading with little/no further exploration.

1st Author	Year	Systematic sequence of operations	Taxonomy and categorisation	Significance of Quantitative Information	Significance of Qualitative Information	Selection with respect to other component types	Use of formal decision-making processes
Graessler	2018	*		*	*		
Gausemeier	2002	*		*	*		
Mlambo	2018	*		*	*	*	
Pahl	2006	**	*	**	**	*	*
Graessler	2020	*		*	*		
Habchi	2016	*	*	***	***		
Zante	2010	*		*	*		
Melville	2014	*		*	*		
Hehenberger	2010	*		*	*	**	**
Zheng	2017	*		*	*		
Cebon	1997	***	***	***	**		*
Salem	2014	**		*	*	***	
Hubka	1988	*	**	*	*		
Ashby	2005	**	*	**	*		

Degree of support for column heading's influence on component selection

Strong	***
Moderate	**
Weak	*
No reference	

Figure 17: Significance of literature on selection of engineering entities to selection of components. Legend denotes strength of relevance to component selection solution.

2.4. Categorisation and Taxonomy in Component Selection

Hubka has previously raised concerns about the lack of **systematic** knowledge in engineering in general:

> *"It is somewhat surprising how little systematic knowledge exists about the nature of technical objects such as tools, appliances, machines, etc."* (Hubka, 1988)

It has also been highlighted how in selection tasks hierarchical taxonomy (see figure 15) is an important consideration (Cebon & Ashby, 1997). This supports suggestion that a lack of systematic knowledge would affect the quality of outputs produced by engineers in selection tasks; with better understanding and view of candidate solutions comes better results, reached more quickly, and with greater confidence in solutions produced (Hubka, 1988). These foundations support the need to review in greater detail on this subject, with particular focus on relevance to component selection.

Any eventual solution proposed which would be required to guide engineers in selecting the right components, representing different component types in categories which were both *logical* and *in keeping with formal consensus* would be a great asset to that prospective solution. It had been envisaged that a hierarchical taxonomy would be a sensible way to achieve this, something found to be corroborated in seminal literature (Cebon & Ashby, 1997). Review of existing categorisations directly relevant to component selection further supported this (Poole & Booker, 2011). Other research also made similar allusions (Zupan et al., 2002) (Siang Kok Sim & Yiu Wing Chan, 1991) (Cheng & Rowe, 1995), though without the detail provided by Poole *et al*. (2011).

Categorisation review has been conducted across a range of subject matter, from robotics taxonomies through to actuation and component taxonomies. Review of this content enabled clarification of the existing categorisation which previously existed relative to component types available, though little was added in terms of published developments pertinent to this work aside from that found in core mechanical design tests (Shigley, 2017) (Childs, 2003). This highlighted issues in terms of the gaps, owing to absence of taxonomy on component types of interest to the type of actuator being developed or failure to keep taxonomies up to date with latest technologies available. In light of literature's recommendation of hierarchical taxonomies, this has found to be something which is absent from literature in a meaningful way that would support component selection and definitely not represented in a *comprehensive* (Cebon & Ashby, 1997) fashion. Ontologies have also been reviewed in the interests of rigour, as they can be considered rule-based taxonomies (Nilsson et al., 2009) (Chandrasekaran et al., 1999); however, limited benefit has been gained from this process.

2.5. Strategies and Tools Utilised in Robotic and Mechatronic Systems Design

Numerous insular approaches supporting selection of individual component types exist, especially for motors (Hughes, 2013b) (Bhatia, 2014) (Zeraoulia et al., 2010) (Esen et al., 2016); however, it is noted that none support selection with respect to other sub-systems of components. These operations are generally useful in outlining key considerations in terms of the need to account for speed, torque, intermittent torque, power requirements, inertia-matching, etc. In a system such as a robot, interaction with other components and actuators is critical. Other instances are encountered which deal with very nuanced elements of selection (Meoni & Carricato, 2018).

2.5.1. Component Selection Frameworks and Methodologies;

There are a limited range of component selection guidelines found in literature, including very high-level processes derived from Ashby's approach to materials selection (Harmer et al., 1998) with greater focus on novel elements of a graphical representation tool developed. Carlson (1996) has also created a high-level guideline set, where specific guidance is considered to be absent. High-level approaches have been developed by government publications for parameter optimisation (McCoy, 1996). Others have outlined the key components necessary for software enabling effective component selection (Culley & Webber, 1992a)., with one instance proposing both a high-level solution and showing how that can be extended to greater degrees of granularity (Vogwell & Culley, 1991). Others have went to greater detail, but lack specifics in terms of tools to use and operations to employ (Agarwal et al., 2007) or focus on optimisation of specific parameters (Akhtaruzzaman et al., 2011). Several of these instances are provided in appendix A.2.

Perhaps the most detailed guidance is provided is a method based on historical data used to make estimates (Cuttino et al., 2010), which make it somewhat idiosyncratic in terms of more ubiquitous component selection; figure 18 provides an overview of the "actuator selection method" developed in this work. Notably, this approach leans of similar themes identified as being of interest, in section 2.3. The significance of requirements at the outset, the need for "requirements weighting", the significance of governing equations and actuator data for manufacturers, etc. are all accounted for.

Absence of structured processes in technical system design are commented as an issue generally (Hubka, 1988) (Gerhard Pahl et al., 2006), and it is considered that there is also an absence of supporting processes in component selection.

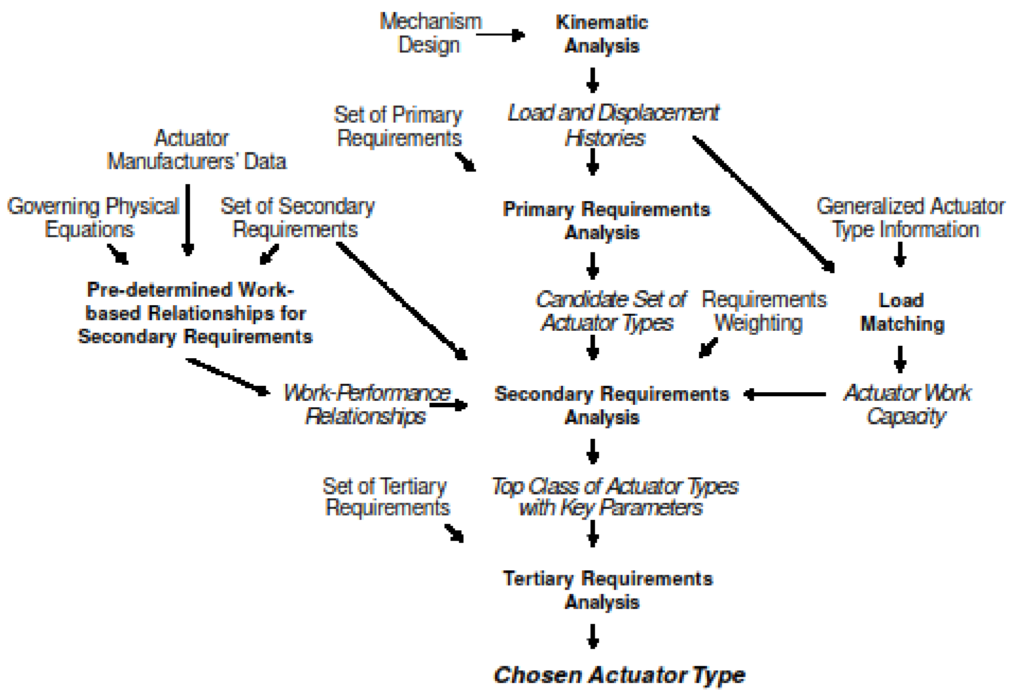

Figure 18: "Actuator selection method" (Cuttino et al., 2010).

Similar problems with component selection are noted in other industries, particularly for software component selection (Ernst et al., 2019) (Lin & Zhang, 2006) (Fahmi & Choi, 2009) (Calvert et al., 2011) (Baker et al., 2006) (Silvander, 2018) (Hamza-Lup et al., 2008), with frameworks and strategies proposed to assist in these instances (Konys, 2015). Review have been extended to these instances as a means to perhaps inspire an alternative view of how engineering components could be selected.

2.5.1.1. Selection Strategies Employed for other Engineering Entities;

The main approach encountered in materials selection employs graphs to represent material performance across a range of criteria (Ashby, 1992). Ashby's approach to materials selection is seminal and utilised extensively with its accompanying software package (Cambridge Engineering Selector; CES). The method works by representing material performance criteria on an X-Y plot, facilitating intuitive comparison.

The graphical approach to component selection developed by Ashby proved to be very successful insofar as the idea is utilised as a successful piece of software to this day. Additionally, many core mechanical design textbook's defer to or heavily reference Ashby's work (Shigley, 2017) (Collins et al., 2010) (Childs, 2003). The most critical part of this approach is arguably the selection charts leveraged. These are discussed in specific detail in section 2.5.2.

2.5.2. Component Selection Tools and Methods

From section 2.1.2.1., both qualitative and quantitative information on component selection should be of significance a component selection solution. This has been reflected in the research focus detailed in section 2.3.

2.5.2.1. Supporting Interrogation of Quantitative Component Information

Tools to assess quantitative parameters of prospective solutions are found in both industry and academia. Both with be assessed in this section, beginning with commercially well-established solutions. Discussion of novel, less well-developed solutions will be covered latterly in this section.

<u>Industrial Solutions</u>

There are a number of modern tools and methods for selection of components used in industry; however, it is observed that these tend to be predominantly centred on motor selection. Many motor manufacturers provide their own platforms for selection of motors, one of the most comprehensive of which is that of Oriental Motors, see figure 19. This platform allows user to configure the system, specifying loads, materials, and geometries, etc. and facilitates auto-calculation of the motor parameters needed. This extends only to OM's motors and doesn't consider other component types, which clearly excludes a large range of solutions. Other similar systems are available (Hampshire, 2020), again specific to OEM's hardware, not extending to all component types. The utility of these systems is not disputed, but they are limited in their extension which is an issue well-documented in literature (Vogwell & Culley, 1991) (Vogwell, 1990).

Other solutions are provided, which are observed to be less effective. Maxon Motors provide a tool analogous to the RS Components selection approach, which utilises drop down menus. This menu is often cumbersome and since the range of options in Maxon's drop down menu is limited at pre-determined intervals, the utility is also hampered; see figures 20 and 21. This also only considers Maxon Motors products, an issue outlined as a problem several times already. RS Components operates as a fairly typical example of a supplier's website, with drop-down menus utilised for selection of components, see figure 22. Due to dealing with various manufacturers, RS Components do not typically present the information in a manner which is standardised and easily interpreted, requiring much user conversion of units. From extensive experience, RS Components information is often found to be out of date, absent or incorrect when compared with specific datasheets, an issues which extends to other suppliers too. Lack of consistency of units is also noted as a problem in current tools, an issue documented extensively previously (Harmer et al., 1998) (Vogwell & Culley, 1991) and raised as a particular issue to be avoided in selection tasks (Cebon & Ashby, 1997).

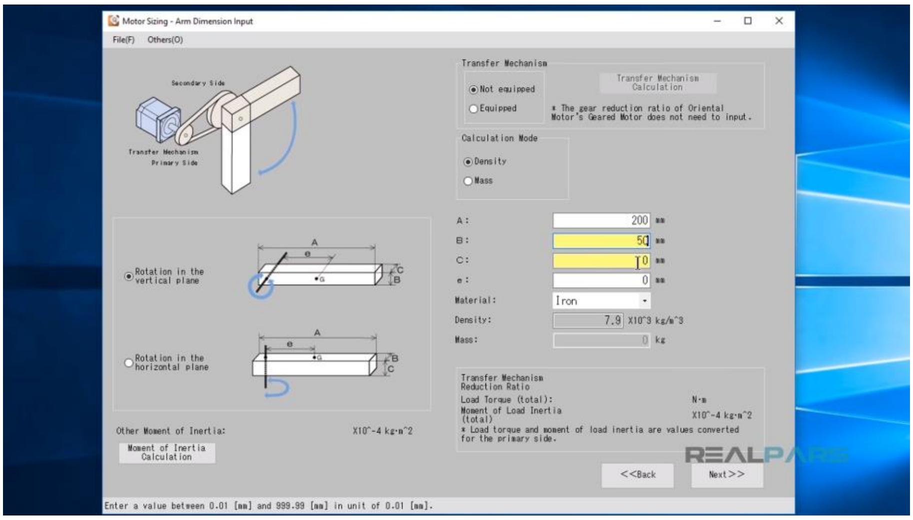

Figure 19: Overview of use of Oriental Motors software, which allows input of qualitative information on performance required from motor.

Across all platforms, search results are always provided in a "catalogued" format, as in figures 21 and 22. This is something which has previously been remarked previously (Vogwell & Culley, 1989) as a potential impedance to effectively relaying information. For example, figure 21 is a refined list of options for a given task, but there's still great variability in potential solutions – and this is for only *one* manufacturer's products. This issue is further emphasised when dealing with unit conversion requirements and user interfaces which are unintuitive or do not provide suitable scope for manipulation of criteria values.

On gearbox selection, it has not been possible to find tools and methods which are specific to the selection of gearboxes, though manufacturers guidelines have been encountered which are somewhat helpful (Power_Jacks, 2020). Bearing selection is also littered with similar problems. For example, SKF provide a calculator, as shown in figure 23. This is helpful in setting up the situation it will be used in (similar principle to the Oriental Motors selector, figure 19); however, as all solutions are SKF products it again doesn't present all options available. Furthermore, there is a reasonable amount of assumed knowledge: one of the first steps is to define the type of bearing required, and without expertise in the applications of different bearings and how they perform relative to one another, this seems an odd place to begin. Even experienced engineers are unsure of best use of self-aligning versus angular contact bearings, so less-experience engineers may struggle greatly without better guidance. A main competitor of SKF, NSK, also seem to have a fairly cumbersome interface for bearing selection.

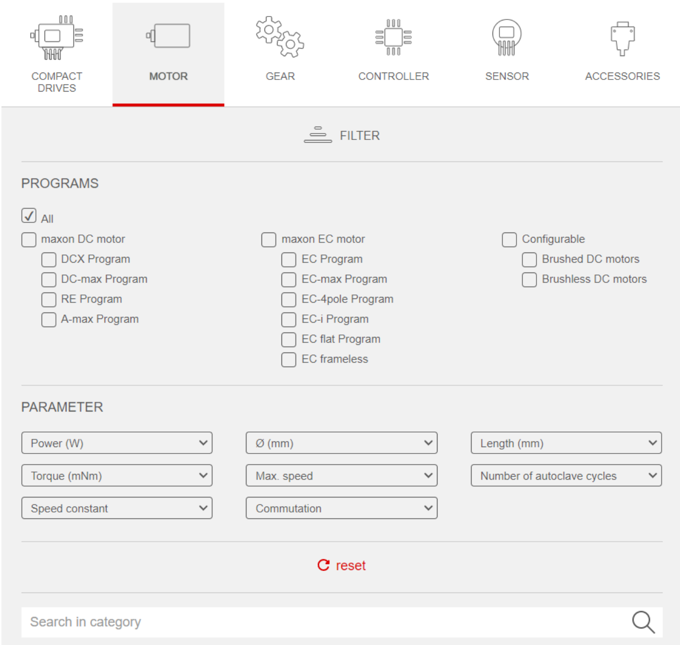

Figure 20: Maxon Motors component selection interface.

PART NO.	ARTICLE	TECHNICAL DATA Ø	P	U_N	N_0	M_N	PRICE
625854 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors	60 mm	100 W	12 V	3760 rpm	261 mNm	€105.64
625855 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors	60 mm	100 W	24 V	4300 rpm	269 mNm	€105.64
625856 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors	60 mm	100 W	48 V	4020 rpm	298 mNm	€105.64
625857 NEW	EC 60 flat Ø60 mm, brushless, 150 W, with Hall sensors	60 mm	150 W	12 V	3760 rpm	378 mNm	€110.91
625858 NEW	EC 60 flat Ø60 mm, brushless, 150 W, with Hall sensors	60 mm	150 W	24 V	4300 rpm	401 mNm	€110.91
625859 NEW	EC 60 flat Ø60 mm, brushless, 150 W, with Hall sensors	60 mm	150 W	48 V	4020 rpm	437 mNm	€110.91
625860 NEW	EC 60 flat Ø60 mm, brushless, 200 W, with Hall sensors	60 mm	200 W	12 V	3760 rpm	492 mNm	€117.82
645604 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors and cables	60 mm	100 W	24 V	4300 rpm	269 mNm	€109.00
647691 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors and cables	60 mm	100 W	12 V	3760 rpm	261 mNm	€109.00
647692 NEW	EC 60 flat Ø60 mm, brushless, 100 W, with Hall sensors and cables	60 mm	100 W	48 V	4020 rpm	298 mNm	€109.00

Figure 21: Typical output of search. Broad range of solutions, not easy to cross-compare against other criteria.

Across all of the component selection interfaces considered, almost all of the same problems documented in literature from ~30 years ago (Vogwell & Culley, 1991) are still inherent. The best tools for component selection encountered are employed by manufacturers, which leaves issues with these methods omitting a large portion of the available components. This raises a major issue with the comprehensiveness (Cebon & Ashby, 1997) of databases being interrogated, which can be argued to invalidate or be hugely detrimental to the subsequent “screening” and “supporting information” steps known to be taken in selection activities. Considering a large volume of components will make catalogued/listed breakdown of available components extremely annoying, hence the utility of graphical representation.

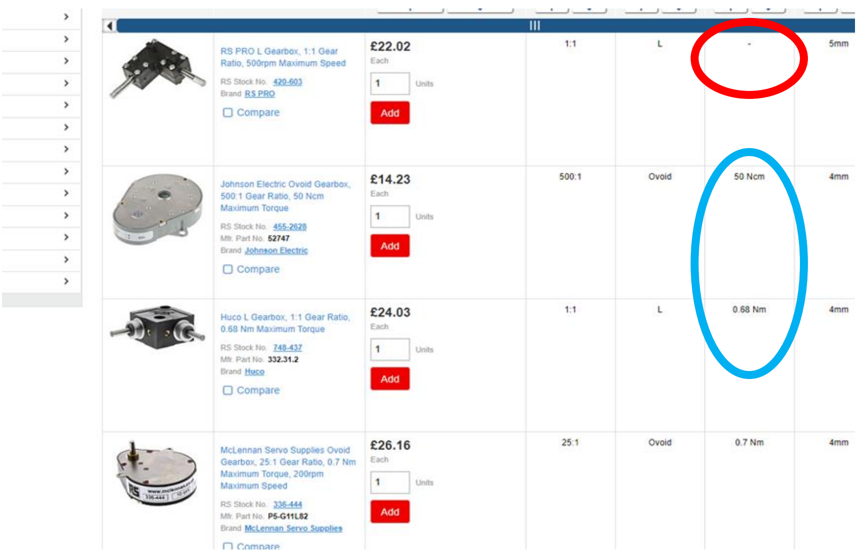

Figure 22: Overview of RS Components interface for component selection. Note missing information (red highlight) and lack of consistency in units utilised (blue highlight).

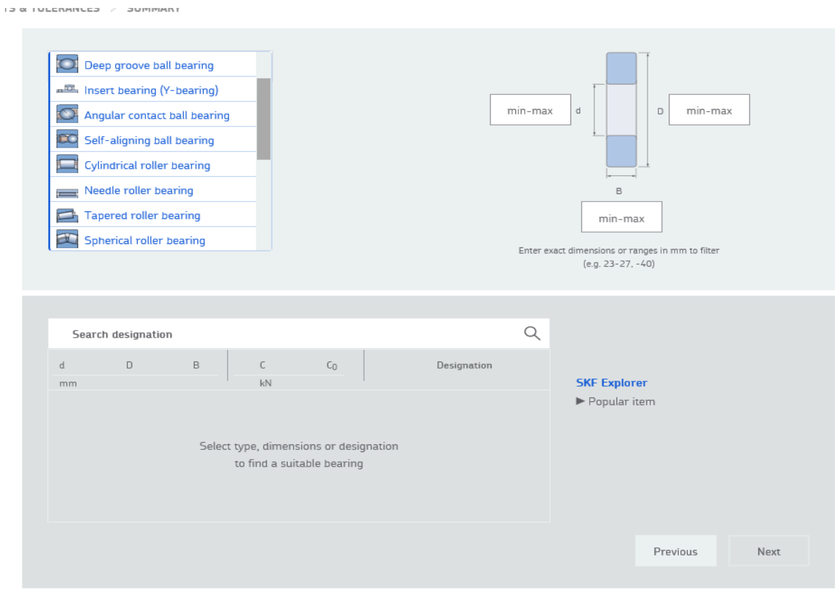

Figure 23: Bearing selection calculator by SKF.

From the researcher's experience, suppliers tend to have the many issues with interfaces subject to the following issues frequently encountered:

- Varied units for one criteria in search results; i.e. *Ncm*, *Oz-in*, and *Nm.*
- Units used are not relevant to region; i.e. torque as '*lb-in'* rather than '*Nm'*.
- Suppliers don't carry certain component types.
- Suppliers still have a largely incomplete database of the products *available on the market*; they only carry the items they *stock*.
- Unintuitive and confused interface for selection.
- Changing interfaces from supplier to supplier.
- Absence of datasheets with some components.
- Actual component performance from manufacturer's datasheet has been incorrectly transferred to supplier's database. In these instances, an already sub-optimal process for component search is destroyed by invalid results, wasting time.
- Other more minor issues.

The above has been compiled from review of existing approaches and experience. Comparison with other, previously published academic literature shows substantial overlap:

(1) "Systems are manufacturer-specific.

(2) Systems are product-specific, e.g. "batteries" rather than "electrical energy sources".

(3) Paper-based methods are tedious and time consuming.

(4) Computer-based methods can give "all or nothing" search results.

(5) Data presentation formats vary from catalogue to catalogue.

(6) *Designers cannot easily see the effect of changing the selection criteria.*" (Harmer et al., 1998)

An extremely similar set of points are made by Vogwell (1991), showing evidence of a trend among methods used over the last several decades which have been ratified by current observations. On this basis, there is a clear requirement for databases which are comprehensive, intuitive to use, and display consistent units, etc. Figure 15 previously outlined many of these requirements, whilst the points made above supplement these assertions with component selection specific criteria.

Academic Solutions

Commercial solutions are found to rely heavily on "tick box" and "drop down" selection options. Within academic literature, there are noted to be remarkably few tools to support selection processes. Those which are encountered rely on graphical representation of component performance, with almost all found to draw direct inspiration from the extremely successful use of graphs in materials selection (Ashby, 2005), which has been briefly alluded to already.

The earliest efforts which sought to explore this phenomenon are noted in the late 1990s, where selection of energy sources such as batteries (Harmer et al., 1998) and linear mechanical actuators (Huber et al., 1997a) were trialled using a graphical approach. Figure 24 illustrates examples of these instances, where graphs representing battery performance are shown to represent the ranges of component performance (only approximately, which introduces inaccuracy) (Harmer et al., 1998), whilst Huber has taken the approach of providing only the limits. Absence of specific instances also inhibits this process being followed through to fruition. This is of importance as it has perhaps not been studied at that level of granularity, whilst absence of that level requires selection to move to a different format, meaning the overall selection process relies on two different selection methods, complicating things.

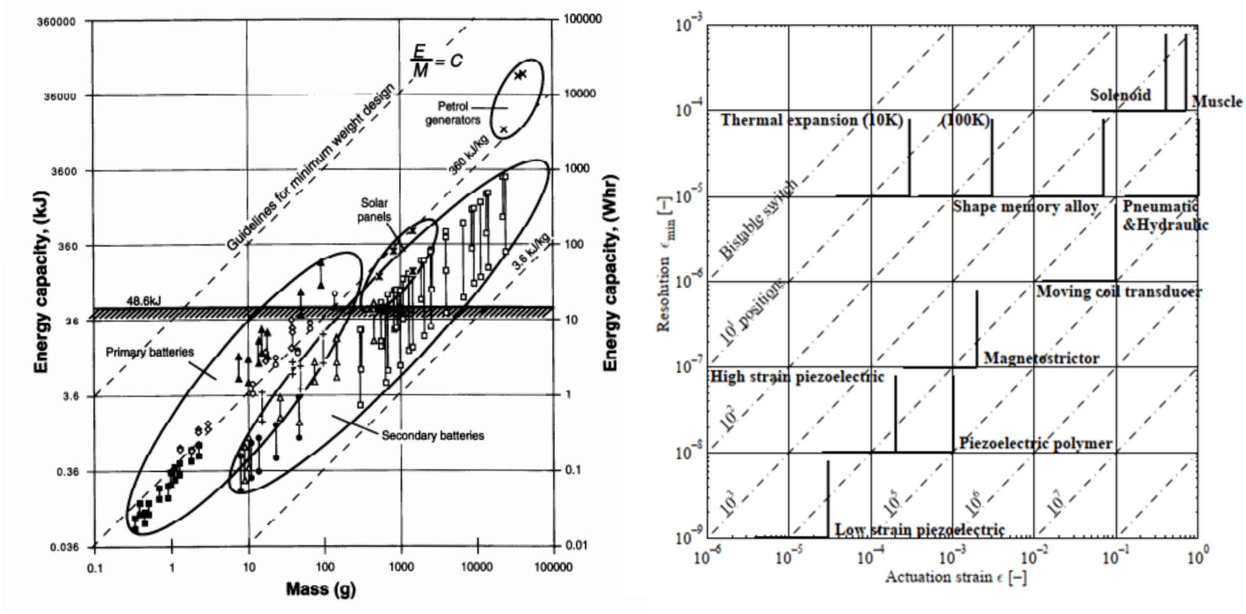

Figure 24: Component selection graphs for Batteries (left, Harmer (1998)) and linear mechanical actuators (right, Huber (1997)).

Cuttino (2010) relied upon graphs mostly as a means to derive relationships between criteria for linear mechanical actuators, and to a lesser extent as a means to support interrogation of these graphs for selection. This is illustrated in figure 25. This work focuses on criteria relationships and leverages graphs as a means to aid this work, rather than supporting selection through a graphical interface, as proposed by Huber (1997), Harmer (1998) and others in the remainder of this section.

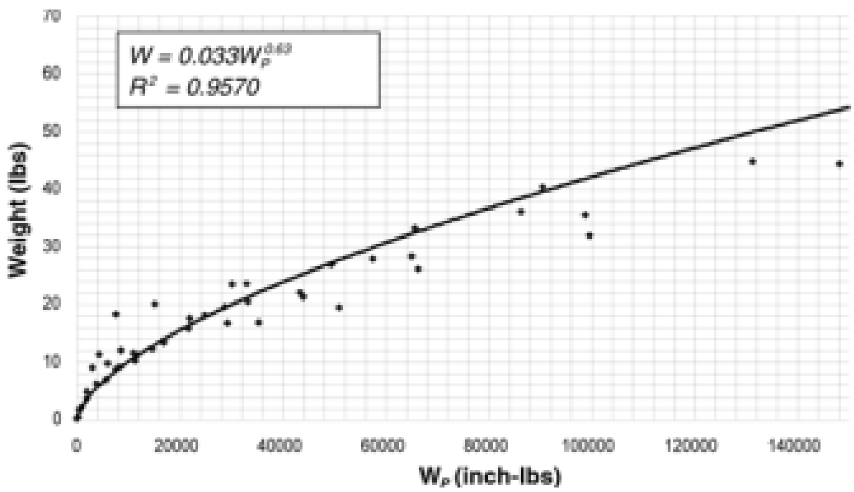

Figure 25: Cuttino's use of graphs for curve fitting to derive relationships.

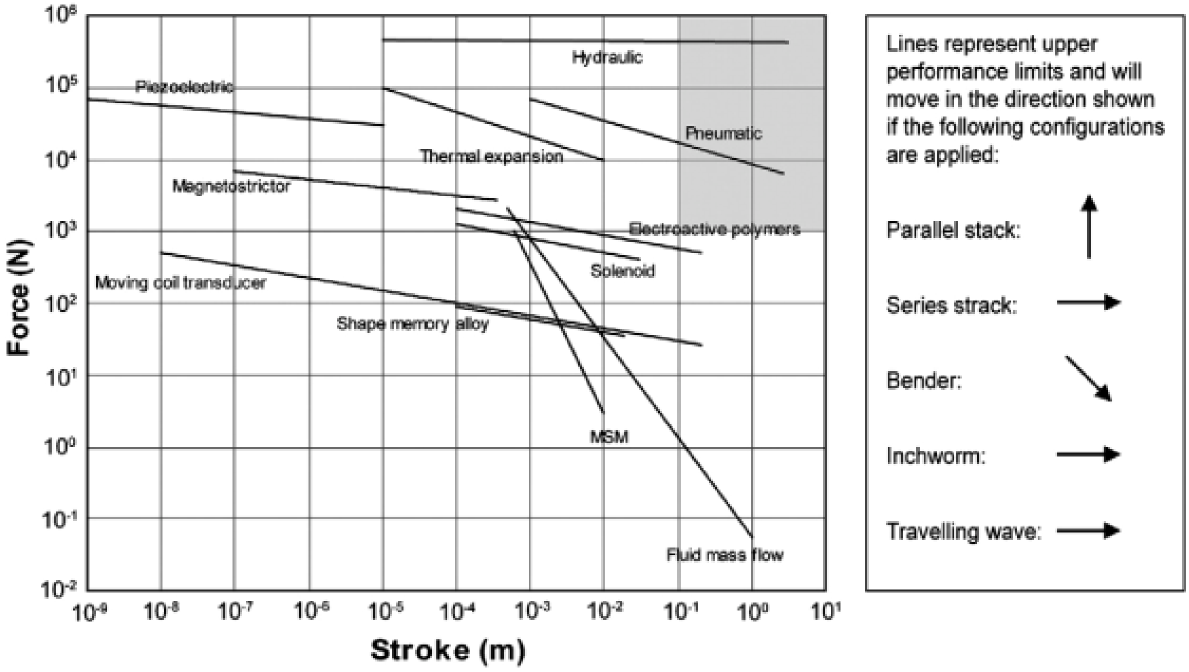

Figure 26: Poole (2011) line representation to performance of linear actuators.

Another example of graphical approaches being utilised to demonstrate performance capabilities of linear actuators is provided by Poole (2011), figure 26, where single lines are used to communicate performance. The line graphs demonstrate the upper performance limit across a range of linear actuators. Notably rotational actuators don not seem to be well-represented. Thematically, the instances covered so far from literature also seem to overlook going beyond the highest level of granularity, where none facilitate selection of a component instance.

The approach proposed may be useful in supporting the selection of linear actuators in the screening phase of a selection process; however, upon the need to review “supporting information” the tool to be interrogated would be required to change. Solutions in this section have limited sample sizes, which affects the comprehensiveness of the solutions, raising issues regarding use of the approaches developed so far in practice.

Zupan (2002) also proposes the use of graphs to represent component performance as a means to interrogate information during the selection process. An example of the graphs Zupan has used is illustrated in figure 28. Zupan samples only around 200 instances of actuators, across a range of several different types of actuator; there are 20 *types* covered in figure 27, meaning each component *type* only has, on average, 10 instances sampled. Whilst the novelty and idea from Zupan are interesting, this also lacks the *comprehensiveness* earlier outlined (Cebon & Ashby, 1997) as being a necessary component of a selection database, and perhaps even to gain a clear understanding of the effectiveness of the approach. Zupan’s work also is observed to operate at a similar level of granularity to those already considered, facilitating part of the screening activity, but limited in facilitating selection of an individual instance. The premise of representing information in a way similar to Zupan has demonstrated is an interesting and useful one which shows great promise if developed further with a larger sample size, and applied to a larger range of component types.

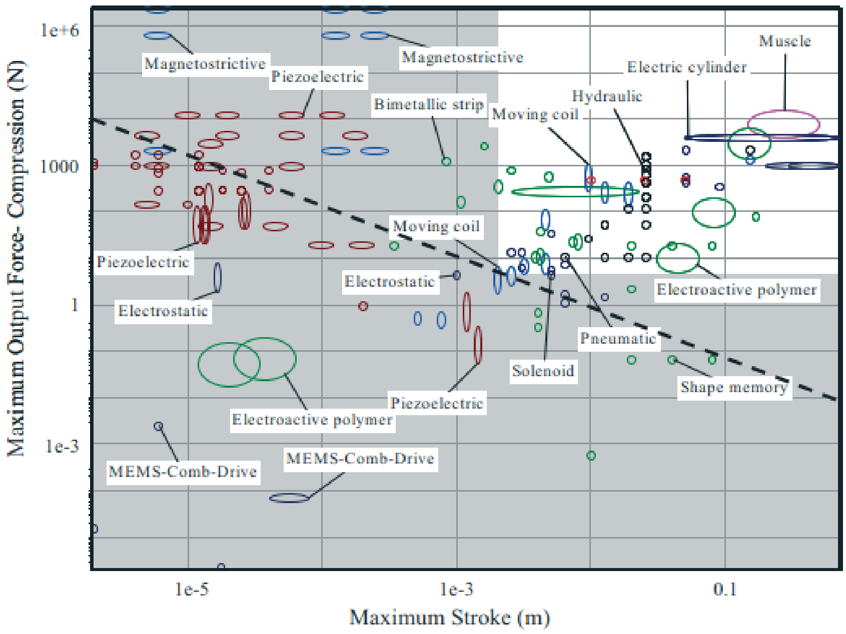

Figure 27: Zupan (2002) proposes use of graphs to interrogate information.

A study by Madden and Filipozzi (2005) covered quite a niche range of actuator types, focusing mainly on experimental technologies (shape memory polymers, shape memory alloys, polymer actuators, etc.), which arguably limits it applicability in terms of real-world design challenges. The study explored use of a web-based actuator tool, and seemed to draw significantly from the work of Zupan (2002) covered previously. An example is provided in figure 28.

Instances have also been encountered which are less directly relevant to the interrogation of component information for selection, but support representation of *other processes* conducted during selection (Hicks et al., 2002). Hicks has also highlighted the significance of component selection as a task, but the approach contributed in addressing problems is targeted at regression analysis as a means to predict costs in component selection at an early stage. Whilst not directly supporting interrogating information to make a selection, it does provide evidence of the utility of conveying engineering information graphically as a means to support the component selection exercise in some format. Shown in figure 29.

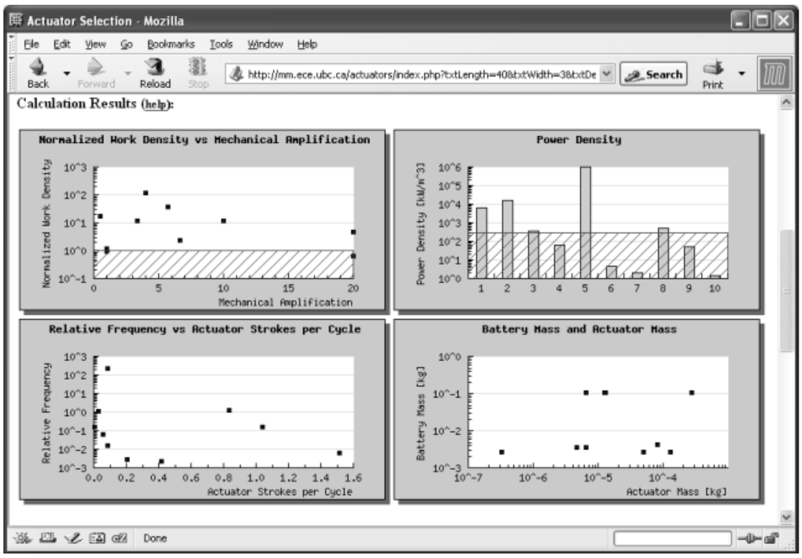

Figure 28: Madden (2005).

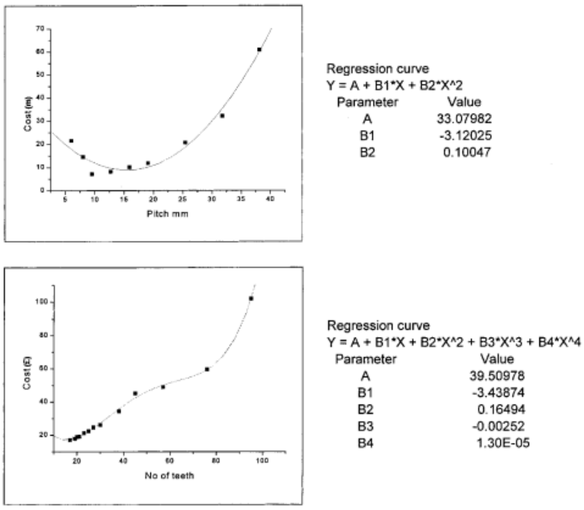

Figure 29: Hicks representing cost-prediction information through graphical communication methods.

It is observed from the most relevant literature in academic publication that *part* of the "screening" process in selection is facilitated by proposed approaches, but refinement down to a shortlist or selection of a specific instance is not facilitated. It is observed that a steady trend of new work in this area across a significant period of time is evident in literature, indicating that many researchers have observed this as an opportunity, though it seems it may be one which has never been developed to fruition as a solution. Previous publication by this work also demonstrates an openness from the research community to accept new work on this idea (Brady & Yan, 2018) (Brady & Yan, 2017).

2.5.2.2. Use of Graphs to Convey Engineering Data

The utility of graphs in conveyance of engineering information is one which is explored in component selection, and it is known from the author's experience to have been exploited to good effect across engineering. To develop clear knowledge on formal publication, use of graphs in conveying engineering knowledge has also been explored extensively.

Ashby Diagrams

In the context of engineering and the conveyance of information using a graphical format, there are also many examples encountered in existing literature. One of the most popular and successful applications of graphs is in the use of graphs do display information on materials to aid in their selection. When representing engineering entities for materials selection, classification of the groupings have been defined as outlined in table 2, below.

Table 2: Definition of hierarchy of groupings in materials selection charts with examples.

Type	Description	Example
Family	The overall *type* of entity being assessed	Materials
Class	A particular case within the type	Metals
Sub-class	A more specific group within the class	Aluminium
Member	An individual specific instance	Aluminium grade 3310

In addition to the description and examples provided in table 2, figure 30 supplements this description to demonstrate how the material types correspond to one another once plotted on an Ashby diagram. Figure 30 draws specific attention to the "checking limits" which can be interrogated for each family, class, sub-class, and member. This facilitates definition of best materials to use from early stages of development of a system all the way through to final materials selection activities. It is an intuitive way of conveying information: in instances where the X-axis and Y-axis criteria are both sought to be reduced, the engineer can quickly check which candidate materials are closest to the origin. Traditional methods may otherwise require inspection of datasheets, etc.

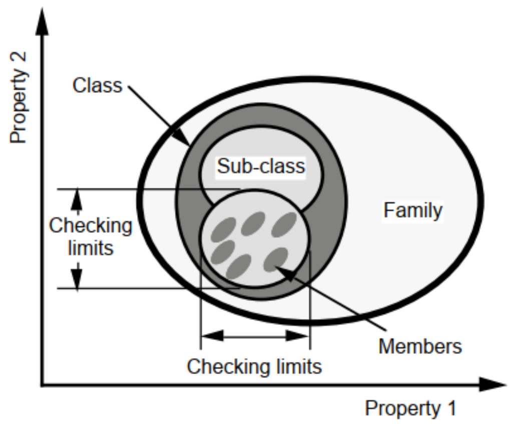

Figure 30: Established terminology for groupings when representing engineering entities graphically (Page 5, Cebon & Ashby, 1997)

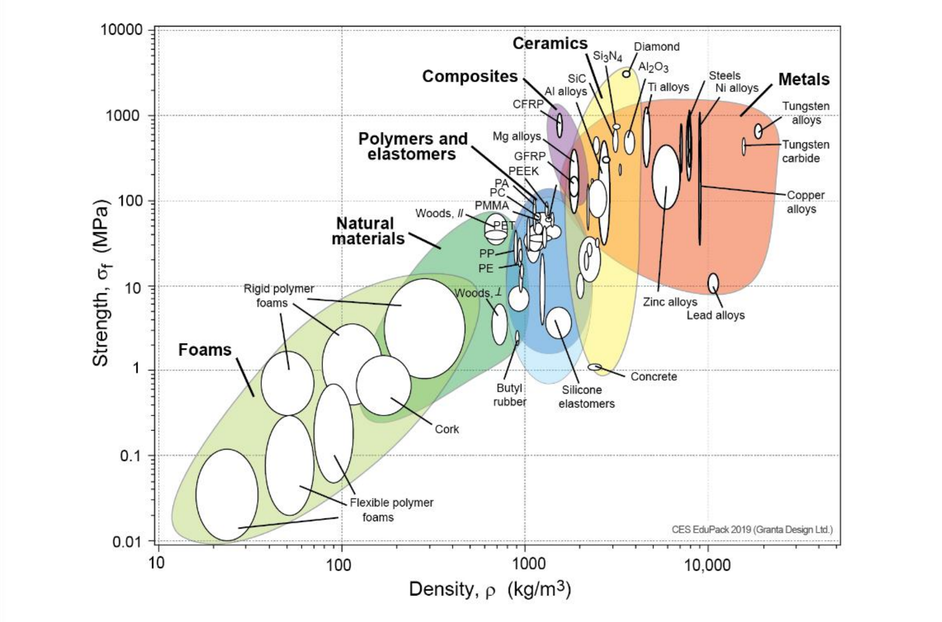

Figure 31: Ashby plot example.

With reference to figure 31, it can easily be seen how an exhaustive population of available materials is a powerful tool in bringing an engineer's attention to a large range of possible solutions, but also as a means to simultaneously convey important information relevant to the parameters of a task.

GOODMAN DIAGRAMS

Goodman diagrams are one of the oldest encountered uses of graphs for the conveyance of engineering information (Goodman, 1899); however, new uses for this method of conveyance are still found in recent publication. The plot provides information to communicate the alternating stress versus the mean stress found in materials, and graphically communicates the number of stress cycles a material can be exposed to before failing.

Beyond communication of the information graphically, the information presented in the graphs has also created opportunity to display relationships graphically too. Gerber lines present parabolic lines based on experimental data, whilst Goodman lines approximate the same relationship in a straight line. This is illustrated in figure 32, below.

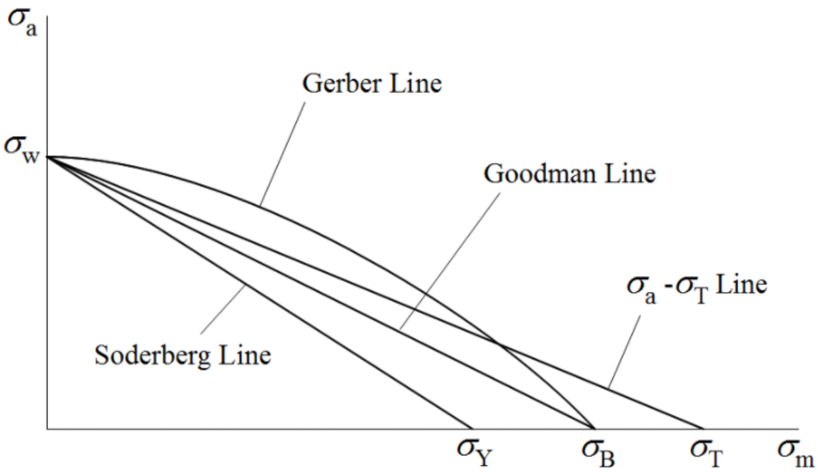

Figure 32: Example of a Goodman diagram, annotated with various information typically assessed using this chart.

TORQUE SPEED GRAPHS

Graphical methods are also used at very specific levels in engineering, as a means to provide information on motor performance variation. Force-torque graphs present information which shows the variation between torque and speed provided by motors, therefore allowing information to also be conveyed relative to the power rating of motors. Such graphs are also very useful in illustrating nominal operating ranges as compared with intermittent operating ranges. See illustration below, figure 33, where an example is given as provided in a typical commercially available brushless DC motor:

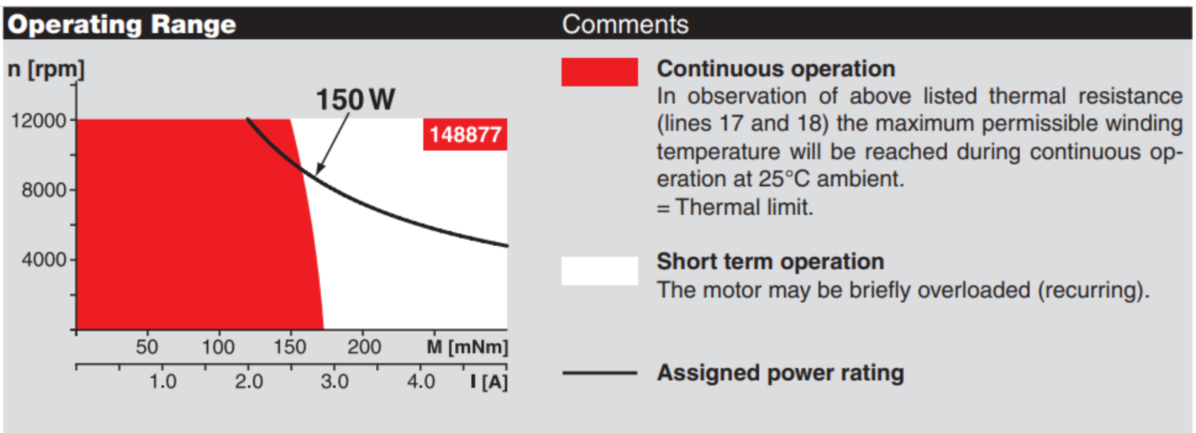

Figure 33: Torque v speed graphs for a motor. Taken from datasheet for Maxon 148877 motor.

This further demonstrates how a graphical means of communicating this information can be very useful; communication of this information would become very cumbersome if attempted without the use of graphs. It is also analogous to Ashby's approach, as the limits of the entity's performance are documented graphically; graphs of this ilk are only useful at the point of selecting a specific instance of a component. Equally, these graphs are often not available for certain components; i.e. Maxon motors provide these for many of their motors, but RS Components typically don't provide this information for their motors.

Further exploration of this idea has covered greater depth of graph use in science and engineering. This is covered in appendix A.3., where examples and supplementary discussion is provided for additional review.

2.5.3. Formal Decision-making Methods in Component Selection

Various uses of formal decision-making methods have been reviewed, initially relying on key literature reviews (Mela et al., 2012) (Jahan et al., 2011) of existing methods and their applications. TOPSIS is understood to allow attainment of best alternative (Lai et al., 1994) (Hwang et al., 1993) to ascertain best alternatives using Euclidean from the best/worst solution (Krohling & Pacheco, 2015). Weighted least square (Chu et al., 1979) methods were reviewed as a means to enable selection, whilst Analytic Hierarchy Process is known to deliver an *ordered hierarchy* (Saaty, 1990) (Saaty, 2013) and is known to have been previously relied upon in materials selection applications (Jahan et al., 2011) and machine acquisition (Page 710, Nof, 2009). Modified direct logic has also been applied to materials selection (Fayazbakhsh et al., 2009) and may be useful avenue to explore further in any solution to be developed based on existing uses (Jahan et al., 2011).

Review of the methodologies and strategies covered in sections 2.1. – 2.4. has also taken place relative to this point, and it is noted that decision-making in selection tends to be mostly left at the engineer's discretion. It has been discussed in section 2.2. how in selection equipping engineers with all the relevant data and a useful format to conduct screening and comparison is viewed as the best approach (Cebon & Ashby, 1997); however, it has not been seen that formalised decision-making tools have been used to guide component selection. Notably, as alluded to in the previous paragraph, various tools are used in selection of materials and manufacturing processes. This demonstrates that there is evidence of use of these methods in making selections in engineering, and may suggest a gap exists in this regard in component selection where a useful contribution can be put forward.

2.5.4. Selection with Respect to Other Components

Existing instances where component selection approaches are holistic have already been commented to lack specificity (Vogwell & Culley, 1991) (Carlson, 1996), as noted in images provided in appendix A.2. For instances examining selection of a single component type the process is complicated by the need to review varying databases (Harmer et al., 1998), whilst throughout section 2.1. and 2.5. it has been noted how little support for the selection or interrogation of databases exists. On occasion where a range of different component types are to be considered, this task becomes further complicated, as the range of information platforms, interfaces, and presentation methods to be interrogated increases too. It has been previously commented how a "common selection procedure" (Vogwell, 1990) is desirable, yet this issue appears to still be unaddressed in commercial and academic solutions proposed. Supplier databases come closest, but are noted to be burdened by only representing stocked items.

Throughout section 2.5.1. a range of component selection solutions have been explored which provide greater detail and specify around the methods used for selection. An issue commented on these approaches is that they focus on one component type. Some examples are those which support selection of batteries (Harmer et al., 1998), linear actuators (Zupan et al., 2002) (Poole & Booker, 2011), or bearings (Siang Kok Sim & Yiu Wing Chan, 1991). Whilst each propose some interesting ideas, it is noted that they are often particular to a specific component type, which raises issues with interactions with other components, particularly when the issue surrounds components which have strong reliance on other component; for example, motors and transmissions are often used in combination, so should perhaps be chosen with respect to one another.

Fundamentally, it is noted from literature that some works would facilitate selection of various component types with little specific guidance, or others support selection of a specific component type with greater detail. Instances which "facilitate" selection also do not *promote* selection with respect to other components, but merely could be leveraged this way if the engineer so chose. It is considered that some solution which *supports* selection of varying component types, with specific reference to other components, and with strong detailed guidance is an opportunity. No comparable works have been found in literature, which presents an opportunity illustrated by figure 34.

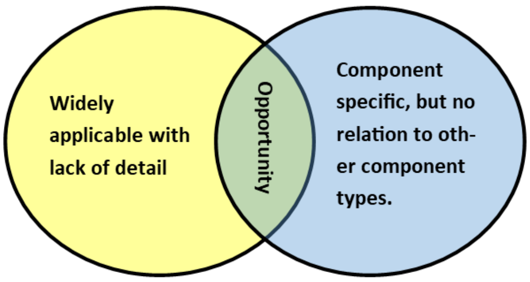

Figure 34: Descriptions of existing approaches to component selection, in yellow and blue. Opportunity for hybrid solution, as highlighted in green.

2.6. Need for New Component Selection Solutions

Across this chapter, the significance of component selection as a central activity in mechatronic design has been established. Key issues and prospective solutions have been explored and illustrated with reference to academic publication and exploration of existing commercial solutions. Review has enabled relevance of component selection to be established at an overall engineering design level, at a mechatronic methodology level, and in-detail with review of specific methods, tools, and approaches.

From review it is clear that no “comprehensive” (Cebon & Ashby, 1997) database exists for component selection, whilst tools and support has also been shown to have issues where new solutions are likely to be possible. Some of the foremost issues identified and ratified by other literature include:

a. Paradigmatic selection – “we’ve always done it this way, so we’ll keep doing it that way”;
b. Biases for entities engineers are more confident utilising, which aren’t necessarily the best solution;
c. Time-consuming process;
d. Lack of awareness of solutions available due to non-exhaustive databases;
e. Need for great experience to be effective in selection processes; and,
f. A variety of issues inherent in other approaches to selection of engineering entities.

These issues are reminiscent of many issues encountered throughout engineering design’s higher-level methodologies and frameworks as well (Gerhard Pahl et al., 2006) (S. Pugh, 1990) (French, 1984) (Ulrich & Eppinger, 1994). Many of the same problems regarding poor understanding of requirements are echoed, along with issues with paradigmatic process adoption, etc. rather than decision-making being led by a robust process informed by a rigorous, systematic process.

These issues have been arrived at following a targeted review, based on review criteria established in section 2.3.1. Others have argued extremely similar points in materials selection in mechanical design (Ashby, 2005), particularly (a), (b), and (e). Point (c) is considered significant in component selection literature (Harmer et al., 1998) (Culley & Webber, 1992a), something ratified in engineering design literature more generally (Gerhard Pahl et al., 2006). Reduction of time lost on processes is clear throughout engineering literature (Peter Hehenberger, 2015).

Component search platforms are noted to be manufacturer-specific (Harmer et al., 1998) (Culley & Webber, 1992a). In modern era, suppliers are not exhaustive in their overview of components available, only what *they* stock. Platforms are often product-specific, rather than system specific (Harmer et al., 1998), something which resonates in modern systems (Oriental_Motors, 2020) (Maxon_Motors, 2020). It has been commented how useful models exist in producing information about component *requirements* (Delbecq et al., 2017), with graphical providence of applicability delineated graphically (Peter Hehenberger, 2012). The absence of a single, standardised format for presentation is remarked upon frequently (Harmer et al., 1998) (Culley & Webber, 1992a) and, with reference to figures 22 and 23, is evidenced to still be an issue.

2.6.1. Specific Gaps in Knowledge

In line with the arguments made throughout this chapter and summarised in section 2.6. so far, the table presented in figure 35 outlines the gaps in knowledge that have been identified. The leftmost column lists the first authors of papers considered most important in this review, whilst the remaining columns list the 7 criteria which have been found to be most relevant to any solution developed, as defined in section 2.3. The significance of each piece of literature to corresponding columns is highlighted in each cell by the key outlined in figure 35, which allows clear conveyance of which works are most relevant to each column.

The colouration of each column, meanwhile, draws attention to the broader picture across *all* literature: this is described in table 3. This evidences that a systematic review has identified significant gaps in the literature in this domain, whilst the volume of literature coupled with existing commercial solutions demonstrates a demonstrable demand for further development in this subject area.

It is proposed that the overall solution to be developed should provide a means to support systematic undertaking of component selection tasks. Findings from review of various criteria has demonstrated that there is also value in developing aids to assist the overall process, as highlighted in figure 35. As a means to specify what the proposed solution should set out to achieve, a prescriptive design specification for the proposed solution is provided in the following section.

Table 3: Key of colour coding and symbols relative to figure 35.

Extent to which literature is relevant	**Colour/ Symbol**
Strongly represented across a range of applications	(green)
Existing solutions, but limited in maturity and/or not applied to component selection	(amber)
Limited range of solutions for component selection. Limited in maturity	(red)
Instance of literature strongly addresses column heading in actuator context	X
Instance of literature partially addresses column heading	O

1st author	Year	Taxonomy and classification of components	Graph use	Guidelines, methodology, or systematic sequence of operations	Formalised approach to decision-making (MCDM, etc.)	Assisting assessment or conveyance of qualitative information	Supporting selection with respect to other components in the actuator system	Use in Actuator Design
Huber	1997	O	X					X
Harmer	1998	O	X	X				
Vogwell	1989	O		O		X		O
Cebon	1997	X	O	X		O	O	
Vogwell	1991			X			X	O
Poole	2011	X	X	X				X
Carlson	1995			O	O		X	O
Ashby	2007	O	X		X			
Cuttino	2000		X	X	O		O	X
Zupan	2002	X	X					X
Kok Sim	1991	X		X		O		
Hicks	2002	O	O	X			X	X
Egbuna	2009	O		O	O	O		O
Akhtaruzzaman	2011			O				X
Begey	2020			O				O
Culley	1992	O		X		O		O
Madden	2005							X
Cheng	1995	X		O		X		

Figure 35: Colourised definition of gaps in knowledge. Enlarged example in appendix A.4. for better readability.

2.6.2. Design Specification as an Outcome of Literature Review

The literature review has enabled deeper understanding of specific technologies and academic literature most relevant to the contribution posed in this thesis. In understanding the existing work already in this field, it has also been possible to identify issues which exist, both through those explicitly outlined by other research and also through implicit understanding developed from issues or absent solutions noted in review of existing literature as a whole.

A specification of key requirements considered crucial to the success of any solution assisting the process of component selection in actuator design has been developed, as shown in table 4. The requirements developed have been able to be specified through review of current state of the art in terms of existing technologies, methods, and strategies applied in the research area of interest, and also through overlap with literature outlined in figure 35.

A substantial body of literature has been found in this area of research, in addition to a range of commercial solutions. This serves as some justification of interest and demand in this area. At the centre of issue identified, existing guidance provided appears to be too high-level, as per sections 2.1. and 2.5.1., in particular. In addition to this, supporting engineers through to selection process (section 2.2.) with useful tools to aid interrogation has been identified as another area of weakness with relatively few solutions. Of the solutions encountered, various novel and promising ideas have been noted which may have strengths as applied to a central solution for component selection. It is considered that many of these promising methods are currently not applied to component selection, have not been developed to their potential, or operate discretely from other tools.

Table 4: Requirements of Required Solution for Component Selection.

Scott Brady Ph.D. Thesis	Requirements list for a component selection solution in engineering design activities	09/08/2020
D/W	**Requirements**	**Responsible**
D D W D D	**1. Support conveyance of qualitative information to users:** - Compile database of relevant information on the component considered; - Capture information from high-level to moderate level. Individual component datasheets can provide specific component-by-component **qualitative** information; - Provide a mechanism to support interrogation of this qualitative information; and, - Provide a format for display/conveyance of relevant information on component types to the user;	SB
D D D W D	**2. Support conveyance of quantitative component information to users:** - Compile database of quantitative information on component types of interest to this study; - Establish a method to support interrogation of this information; - Establish a method to support intuitive review and comparison between prospective solutions in component selection activity; and, - Support process through to selection of individual specific component, based on quantitative performance parameters.	SB
D D W	**3. Provide a baseline categorisation for components considered** - Define the categorisation of components to enable representation of qualitative and quantitative information; and, - Build on previous work to develop up to date and logical taxonomies of components relevant to the selection procedure being developed.	SB
D W W	**4. Support decision-making:** - Provide users with spectrum of information available such that decision-making is supported by allowing review of all relevant information; and, - Where definition of most important parameters is required, provide robust and formalised means of determining criteria precedence	SB
W W	5. **Support selection with respect to other components**: - Selection of components impacts the selection of other components. This interaction should be accounted for and supported in any guidance provided	SB
D W D D	**6. Overall guidance through component selection task completion:** - A solution should build upon previous process flow diagrams and step-wise guidance; - The user's attention should be drawn directly to the most important information required in selection tasks; and, - This design specification has already prescribed the need to explore novel solutions to communicate information. An overall strategy to clearly specify the interactions and steps to take is necessary.	SB

review has provided clarification of gaps in literature, as well as the necessary knowledge basis to compile a requirements list for a solution. Succinctly, this work seeks to establish a new component selection solution, which brings greater rigour and robustness to the process It is expected that this solution will require to draw upon several discrete elements to address all points of the design specification, therefore an over-arching framework is proposed to structure to the overall solution.

3.0. A Framework for Component Selection

As alluded to at the end of section 2.6.2., a framework structure is proposed to support component selection, alongside novel methods which are to be leveraged in selection of components to meet requirements. Sections 3.1. – 3.3. introduce the main methods utilised, whilst section 3.4. illustrates the framework's intended overall function.

3.1. Component Performance Graphs

As per the requirements list detailed in table 4, relaying quantitative information on component performance to enable effective interrogation of this information is crucial to enable effective selection. This has been discussed at length throughout section 2.5.2. in chapter 2, justifying its inclusion as a key requirement in the design requirement list put forward in section 2.6.2..

From review across section 2.5.2., it is noted that graphical methods of representing information have shown excellent effectiveness in communicating engineering information to meet various requirements, whilst the idea has been explored with positive effect for component selection (Zupan et al., 2002) (Poole & Booker, 2011) (Harmer et al., 1998)Harmer. The diverse range of existing solutions used by commercial enterprises tend to rely very heavily on drop-down menus, and interfaces of that ilk, which have been commented to have issues for many years (Harmer et al., 1998). Despite the use of graphs to effectively communicate a range of *other* engineering information (Ashby, 2005) (Huber et al., 1997a), graphical methods are noted to have been largely neglected in component selection with the exception of a handful of exploratory papers in academic publication, as illustrated by figure 35.

The promising results found from initial work in academic literature and extensive success of graphs across engineering and science for tasks analogous to component selection serve as reasonable rationale to support exploration of graphs as a means to convey component performance information. Coupled with the saturated use of drop-down and catalogue approaches used by commercial suppliers/OEMs, the potential value of a novel manner of displaying information for interrogation is enhanced.

Across commercial solutions and solutions found in academic literature, an array of issues are noted to be evident when attempting to undertake *interrogation of quantitative information* during component selection tasks. Expansion of the specifics surrounding point 1 of the requirements list, table 4, are provided:

1. **Lack of relative comparison**: often phrases like "applications requiring constant speed would use the shunt connected motor" (Page 75, Hughes, 2013a) or "…induction motor is usually cheaper" (page 142, Hughes & Drury, 2013) can be found in motor selection literature. Without more tangible discussion of the limits of these systems, or unless the reader has a wealth of experience, graphical comparison may facilitate easier understanding of performance *relative to other options available*. With reference to figure 37, one can ascertain the cost range of DC servos at a given nominal torque and compare to other motor types. This is far more useful than statements like "DC servo motors are expensive";
2. **Absence of a central, comprehensive source of information**: Culley (1997) specifically draws attention to the need for a comprehensive database to enable effective selection. This is noted to be absent throughout commercial and academic solutions. Academic solutions lack comprehensiveness as they stop short of delving into the necessary levels of granularity to support selection of an individual solution and they also often use small samples for their databases. OEM solutions tend to be parochial, only offering a platform to interrogate that which the *individual supplier/OEM* stock sells;
3. L**ack of standardisation of data sheets**: variation in units and presentation formats complicates and slows the process of reviewing quantitative information. Through the proposed solution, it is posed that the use of graphs to convey information can remove this issue. It also potentially facilitates a better platform for unit conversion; and,
4. When trying to choose between several components across a range of criteria, it quickly becomes **difficult to keep track** of what components are better on which criteria points. This is especially true when components are scattered across a range of supplier/OEMs' webpages and catalogues. It is considered that the representation method suggested may help mitigate this issue by providing a comprehensive and centralised platform for interrogation.

Issues have been identified in commercial solutions regarding the ineffectiveness of solutions available there, whilst similar issues have been identified in the granularity and methods used to communicate component performance information in academic publication. As a proposed means of addressing these issues, graphs have been developed to support selection of actuation components in engineering design activities. The development of this approach is explored in the pages which follow.

3.1.1. Development of Graphs to Represent Quantitative Component Performance Information

All graphs developed in this work can be found in this chapter's appendices, whilst select graphs will be discussed at length in this section for the purpose of explaining the developed solution's operation, the steps involved in creating the graphs, and the issues encountered and overcome.

3.1.1.1. Sample Database

Prior to development of graphs to represent the information of interest, it has been necessary to determine what information should be represented and what sources should be used to gather this information. Concisely, there were three points which required definition:

1. What components should be covered by this solution?
2. Of the chosen components, which criteria should be covered by the solution?
3. What sources should be used to create a good quality sample of components and criteria of interest?

These three questions are addressed individually, and exploration and understanding of these issues has been necessary as a means to enable this solution to be developed. These points are, however, considered to support the contribution being made, without being directly critical to the contribution of this thesis. As such, point 1 has been addressed in section 1.5 and appendix B.1.1, point 2 is addressed throughout appendix B.1.2., and point 3 is also addressed in appendix B.1.2..

3.1.1.2. Presenting Graphs

Various issues in presenting the graphs have been encountered and overcome as a means to facilitate this method of interrogating information.

<u>Definition of Most Appropriate Scale</u>

Initially a linear scale was considered for representation; however, it quickly became apparent that this would not be a practicable way to proceed owing to the large variability in criteria magnitudes, this is demonstrated in figure 38. Detail at the extremes (particularly the smaller extremes) is lost, and it becomes very difficult to fit all elements on the scale in a manner which does not bias towards favouring certain component types over others for representation.

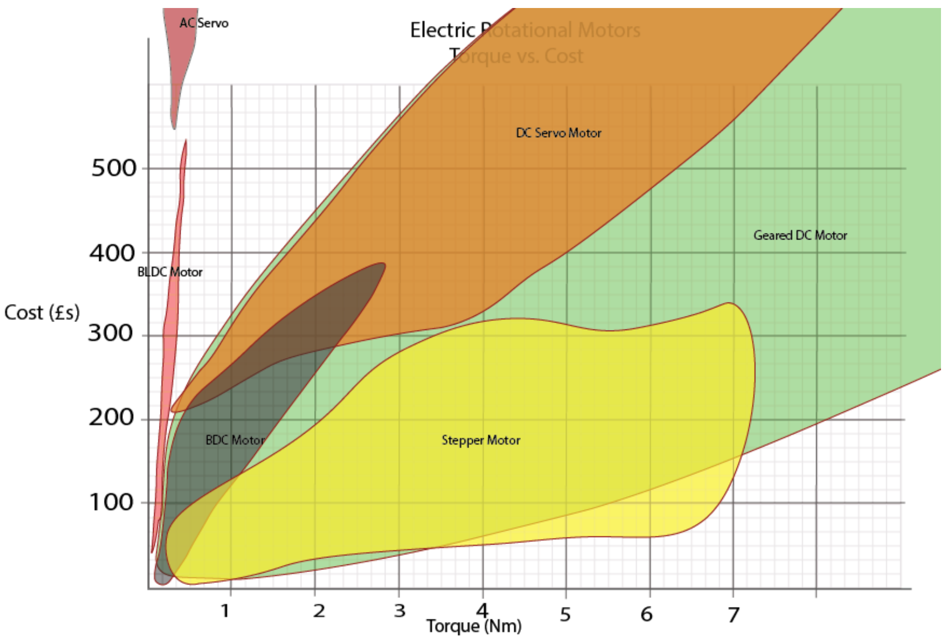

Figure 36: Example of attempt to plot on a linear scale. for torque and cost of electric motors.

To overcome this issue a logarithmic scale is utilised, which addresses each of the points mentioned. An example of this is presented in figure 37, where it is demonstrated that this scale provides far clearer conveyance of component performance across many orders of magnitude, also removing bias towards some components over others.

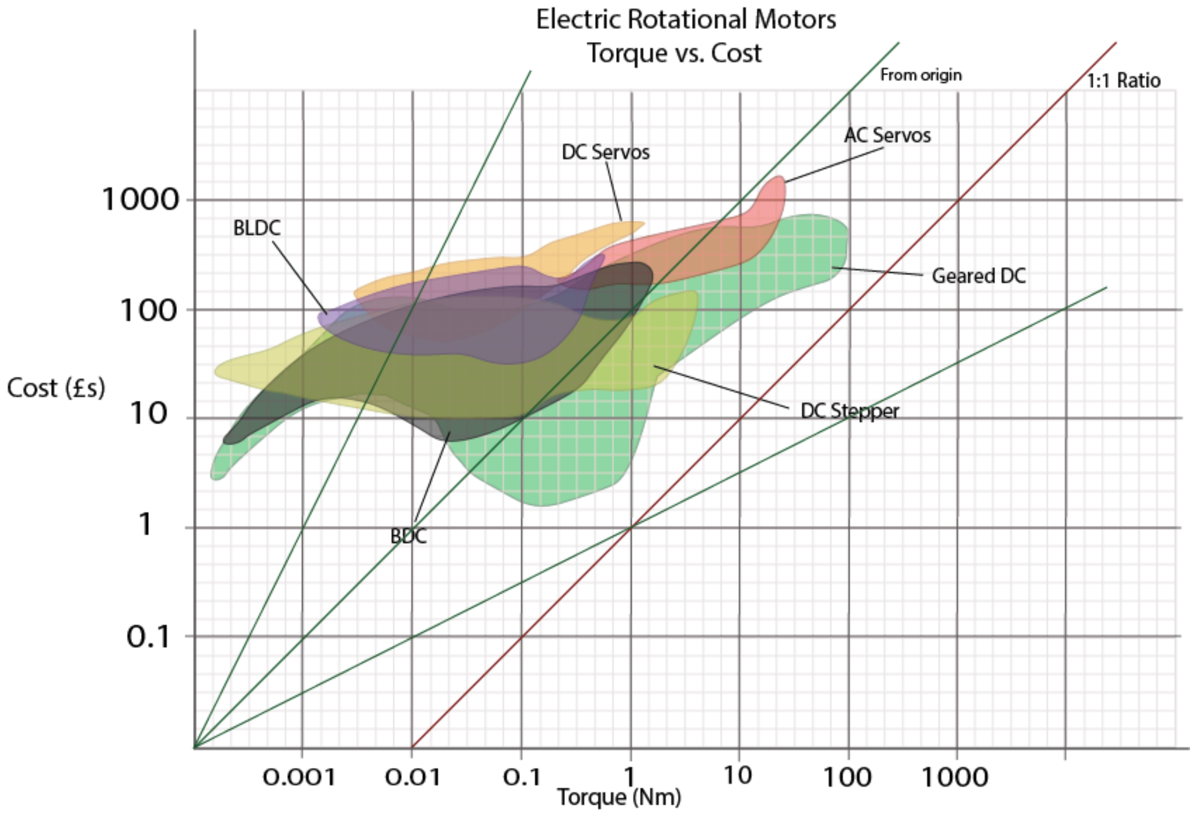

Figure 37: Example of motor criteria as plotted on a logarithmic scale.

<u>Constructing the Graphs</u>

As mentioned, a database has been developed to provide a sample from which the graphical representations could then be built. The database provided a generalised overview of the extremities of the criteria to be represented at varying points. The focus of graphs currently keeps a single criteria on the X-axis and varies the Y-component of the graphs for each component. This being the case, the graphs are constructed by taking the high and low extremities of the X component and plotting these on the graphs. Next, the extremities of Y values at *periodic* X values are sampled. Figure 38 demonstrates this process using geared DC motors (the green bounded region) for torque against mass as an example.

From figure 38, it can be seen that between a torque of 0.001 Nm and 0.01 Nm several X samples are used. At these periodic X samples the Y range is plotted. This same process is completed across the entire X range, which allows a boundary to be created which reflects *actual* performance boundaries of components available to engineers. This differs greatly from any existing works encountered (Zupan et al., 2002) (Poole & Booker, 2011) (Harmer et al., 1998), which only deal with approximate estimations. This facilitates conveyance of better quality information, which is more accurate in terms of the *actual* solutions available to an engineer.

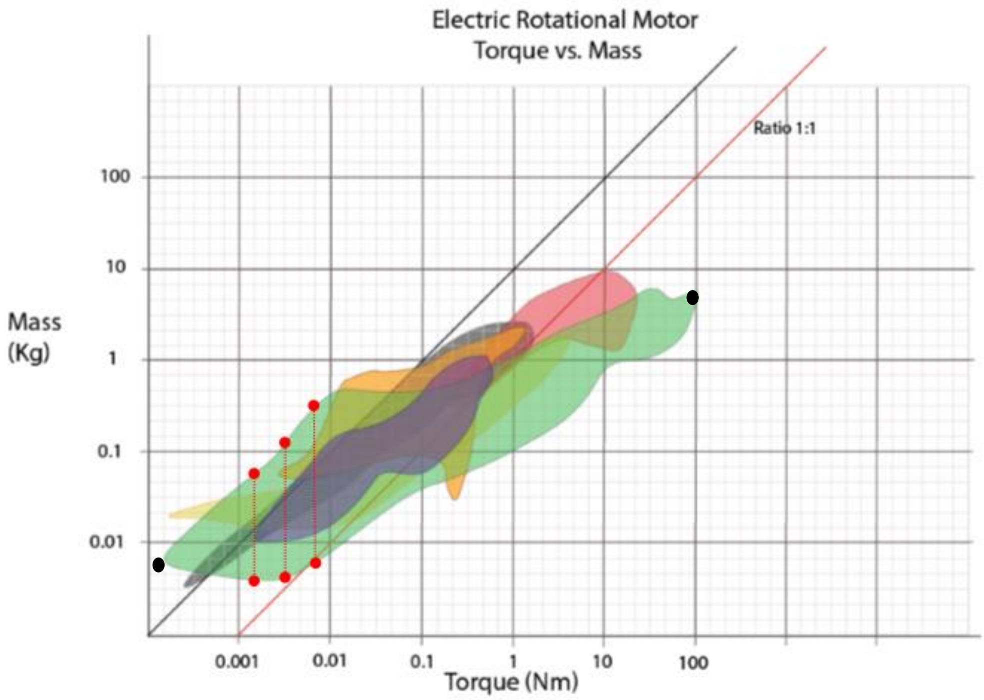

Figure 38: Discussion of how graph boundaries are constructed. Extremities of X elements highlighted in black dot, and y-components' highlighted in red.

This process described for plotting the graphs is next required to be repeated several times for each *criteria* which must be represented. For example, when plotting torque versus cost for motors, the X values of torque will remain the same as in figure 38; however, the criteria, numbering system, and range provided for Y-components will completely change. This is demonstrated in figure 39. This covers changing Y-components within a single component type for a single *family* of components; in the example provided, this is geared DC motors. This process must then be replicated for each component family represented in the motor graphs; i.e. the process is repeated for BLDC, BDC, AC servos, etc.

This is an extensive process, undertaken for *each* criteria of *each* component for *each* graph. It becomes even more extensive after completing for motors, as the next step requires this same process to be applied to development of graphs for bearings, brakes, sensors, and transmissions. A great many bespoke graphs have been developed in this work, with each graph covering an average of 5 components across varying criteria. This does not include graphs which have been edited and utilised in each case study, where the number of unique graphs has grown extensively.

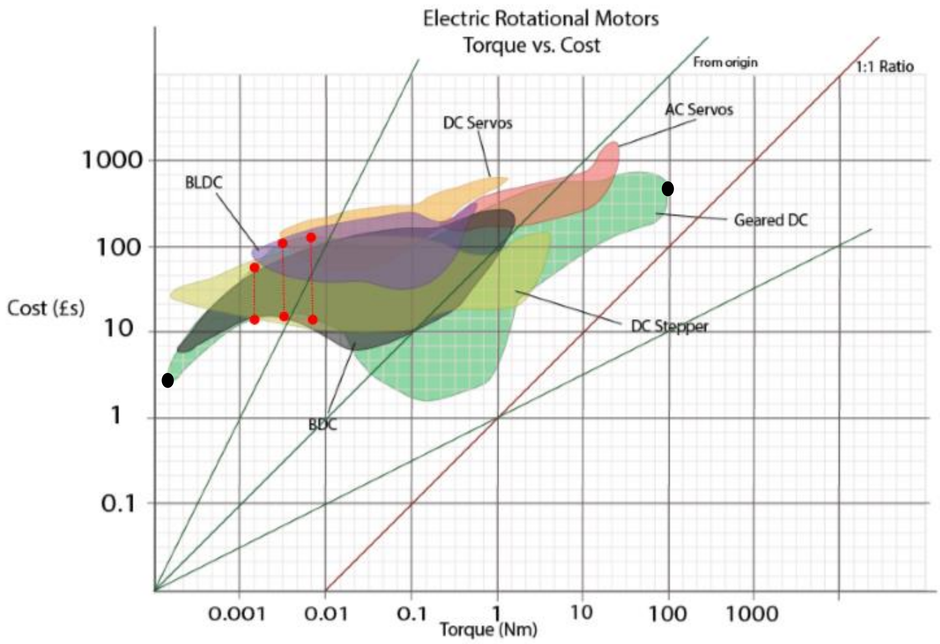

Figure 39: Alternate instance of bounding of geared DC motors. Note change of criteria, change of Y-axis numbering system, and change in Y bounding components for the family shown.

<u>Issues Encountered in Presenting Graphs</u>

A variety of issues were encountered in compiling the graphs, summarised as follows:

a. Sensor graphs were attempted to explore this phenomenon further, but were not successfully developed. Owing to the low numbers of component instances able to be sourced with accurate and complete datasheets for key components such as optical and magnetic encoders, there was too small a dataset to merit transfer into a graphical format. This is not to say that this information cannot be represented graphically, only that the resource limitations of this project have precluded this from being possible in the timeframe laid out.
b. Certain quantitative criteria are deemed unfit to represent graphically. Stepper motor step angles generally range from 1.8° to 18°, so this is covered in qualitative databases for now until a future solution can be found.
c. Representing information on the graphs in an easily viewable manner. Overcome using a logarithmic scale.
d. How to bound the areas of the graphs initially posed problems, but has been overcome as outlined in section 4.2.3.2.1.
e. Availability of component criteria dictates how effectively certain criteria and certain components can be represented graphically. With more available data, the graph representations can be more comprehensive.

3.1.1.3. Performance Indices of the Graphs

This section introduces the utility of the index lines which are shown in every graph developed. These index lines function as markers to show how two criteria relate to one another proportionally. The lines are colourised: green lines are taken "From Origin" and so show a "nominal" proportionality, whereas the red line equates the units of two given criteria at a "1:1 Ratio" (where possible) to give an overview of proportionality of one to the other.

Example

In figure 40, two dots are marked on the graphs; red and black. These dots represent two generic motors, compared against two criteria: cost and torque. They have approximately 0.1 Nm torque.

If the desire is to reduce cost as far as possible, the red motor is the cheapest. If the designer, for some reason, wanted a motor which provides the best torque output *per unit cost* in GBP incurred, they would be encouraged to refer mainly to the nominal "From Origin" line. The 1:1 line exists to give a reference point, but the nominal line is leant on in most applications. The green line shows a constant ratio, which changes depending on the graph being considered. In this example, this line represents a 100:1 ratio of cost to torque (0.1/0.001, as highlighted by blue circle); at all points above the line the ratio is higher than 100:1 and at all points below it is less than 100:1 The 1:1 ratio line shows how two criteria compare when their units are *equated* to give a relative sense of magnitude.

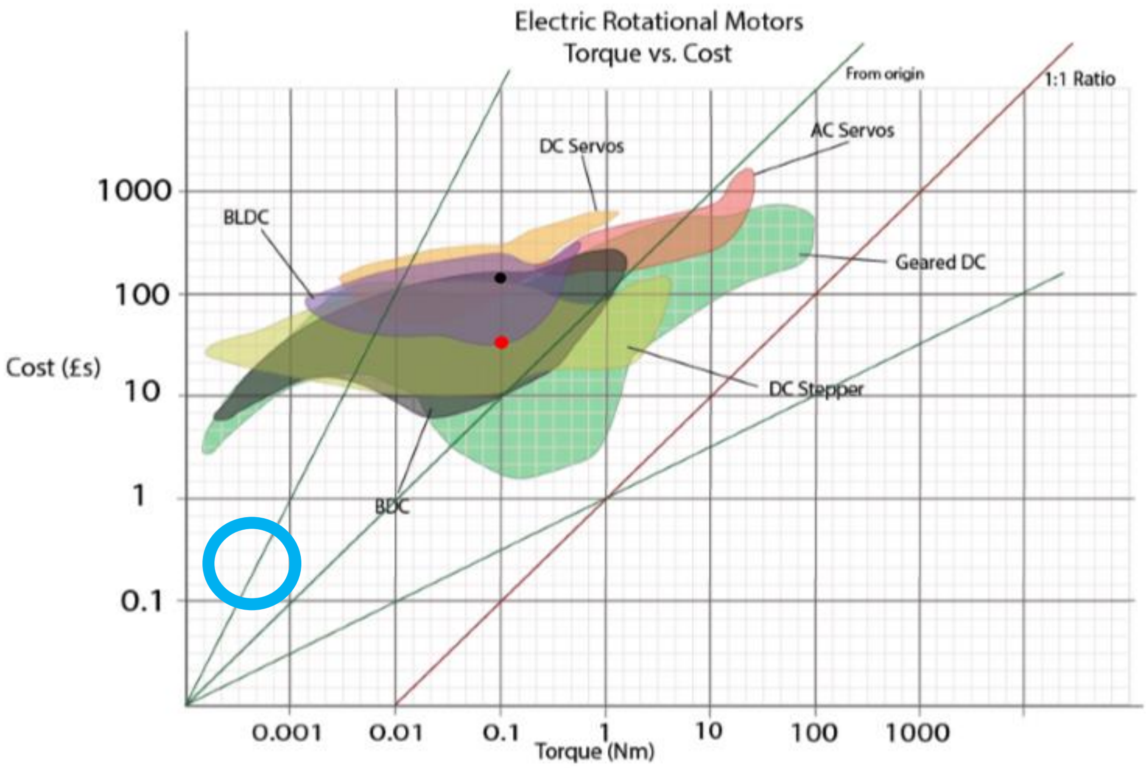

Figure 40: Example of use motor plots.

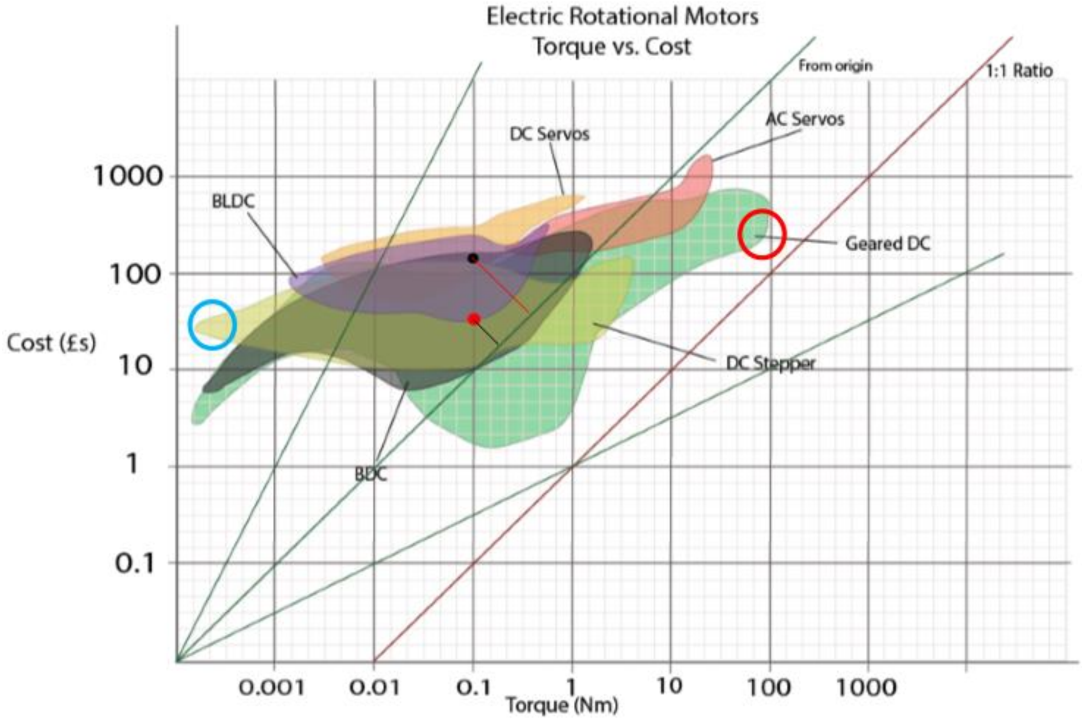

Figure 41: Example of utility of index lines, part 2.

In figure 41, 2 new lines have been added. A red line and a black line. Additionally, a red and blue circle have been added at the torque extremities of geared DC motors. These circles denote the points on this graph at which some of the best (red circle) and worst (blue circle) function-costed solutions exist, assuming the desired output is maximum torque per GBP spent. Motors denoted by the red circle cost around £400, and deliver ~100Nm of torque. This means that a 4:1 ratio exists of cost to torque. Compare this to the red dot (£50 and 0.1 Nm torque; 500:1) and the black dot (~£300 and 0.1Nm torque; 3000:1) and the utility of function costing becomes more useful. Some of the worst instances are stepper motors around the light blue line, costing around £50 and delivering <0.0005 Nm of torque (>100,000:1). Even though these stepper motors are cheaper outright, they are several orders of magnitude more expensive *from a function-costed POV*. There are reasons for this added cost in some instances, which is what qualitative summaries discussed in section 3.2. attempt to account for. Utility of index lines depends very much on the application.

In the context of index lines, the user should work from a line they consider reasonable dependent on their requirements. From there, a component should be chosen with respect to the line. Continuing with the example from figure 41, working with the From Origin line, it is likely that the user *ideally* wants a solution which is **below** the line and the **greatest distance orthogonally** from the line; a low cost to higher torque solution. Where this is not feasible, solutions above the line should be considered and these should be the **shortest** distance from the line **orthogonally**, again attempting to achieve best torque to cost ratio.

Broadly speaking, it can therefore be understood that when seeking good function-costing for the Y-axis criteria, the user should seek something **below** the line and the **greatest orthogonal distance** from the line. That is, the largest distance A, <u>or</u> the smallest distance B, in figure 42. If the X-Axis criteria is being optimised for function costing, the opposite should be applied, as shown in figure 42, below; large C value or small D value.

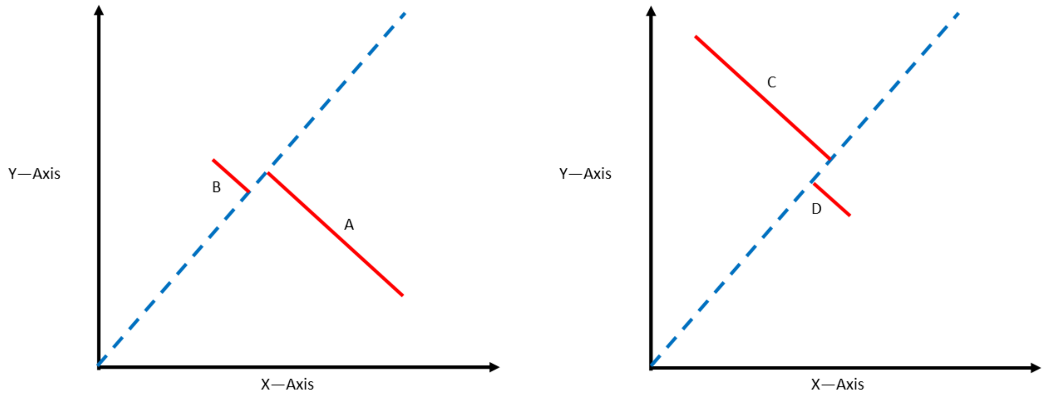

Figure 42: When trying to reduce criteria on Y axis, make distance A as large as possible. If not possible, reduce B as far as possible. The opposite should be followed for the X-Axis.

<u>Algorithm to Determine Best Function-costed Component</u>

There are instances where visual inspection will be sufficient to observe which components align best with index lines for function-costing. As a means to account for instances where this is not possible, to check solutions, and to facilitate later conversion to a software format, algorithms have been developed which will provide an output number to indicate which solution is the best from a function-costed perspective against two criteria.

The process of developing the algorithm to create a value for determining the best function-costed selection was expected to be far more simplistic than it ended up being. Two of the key reasons for this were that the scale is plotted logarithmically, which impinges upon the ability to conduct the calculations linearly. Also, due to the changing component types, the changing criteria, and the changing proportionality between the X and Y axis criteria, there was need to introduce a coefficient for considering this changing proportionality.

Dealing with changing proportionality of X and Y Axes

Sticking with the Torque V Cost graph to ensure continuity, one can observe that the scales for each of their criteria are not the same. It also needs to be acknowledged that the scales change from graph to graph. As such, there's a need to assuage this issue to ascertain the proportionality of one axis to the other. This is done by sampling the first increment of the Y-Axis and the first increment of the X-Axis to attain a coefficient of proportionality for the graph under consideration. This is given as follows in relation to figure 43:

$$n_{proportionality} = \frac{First\ increment\ of\ Y - Axis}{First\ increment\ of\ X - Axis} = \frac{0.1}{0.001} = 100$$

On the basis of this, the *n* value must be *applied to X values* in future equations since they are 100 times smaller. This is to ensure 1:1 proportionality with Y values in determining the index for function-costed component selection. The index is essentially the Euclidian distance between an individual point and the ratio line being used, explaining the need to institute this *n* constant in order to produce a useful index value.

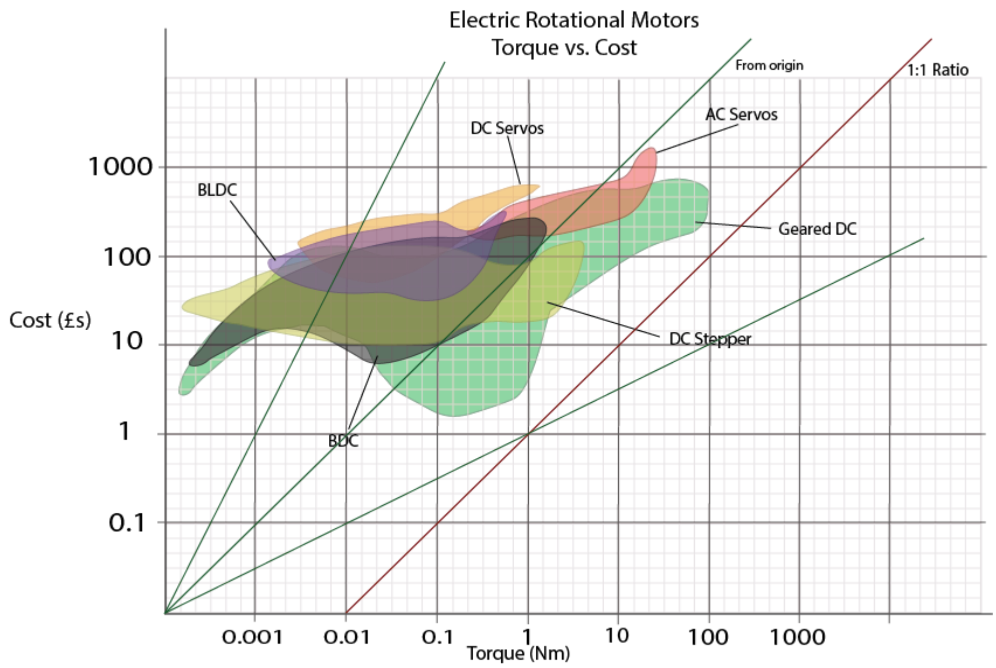

Figure 43: Reference for explaining algorithm.

In future developments, particularly if integrated into a software platform, all increments of the scale could be checked to ensure that the proportionality is the same. If there is an issue then this can be identified and dealt with, as there would have to be an inherent issue within the graph. In software, each components index could be displayed *as a criteria of that component*. Depending on a component's location, it must be found in one of two ways.

Derivation of Selection Index for a Component above the From Origin Line

If *B* is the index of interest for a point above the line, then *B* must be found. The algorithm developed to support this is next presented, whilst figure 44 delineates the elements of the equation being derived.

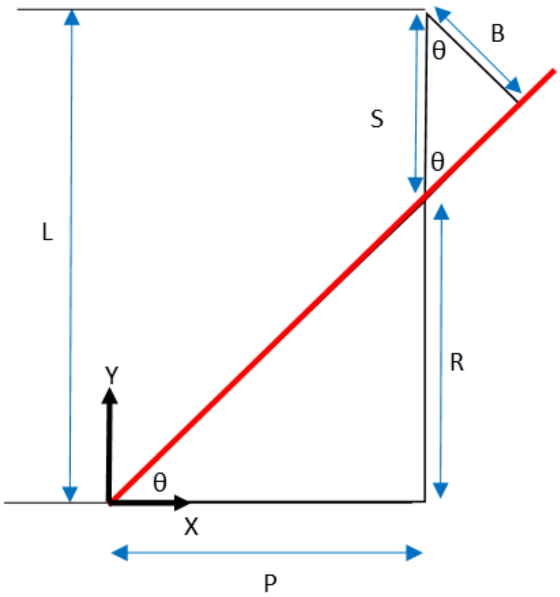

Figure 44: Components utilised in developing a quantitative value for the function-costing index above the index line. X and Y axes denotes, red line indicates From Origin index line.

B is given as:

$$B = \left(L - [n_{proportionality} \times P \times tan\theta]\right) sin\theta$$

Since:

$$B = S \ sin\theta$$

Where,

$$S = L - R$$

Where,

$$R = n_{proportionality} \times P \times tan\theta$$

The information presented above is new content developed in support of this research work. A slight variation is required to provide index calculation for below the line; however, this is summarised in appendix B.2.5. in the interests of avoiding repetitious discussion.

Potential Uses and Applications of Performance Indexes

The use of function-costing serves as a useful tool to early estimation of a system cost (French & Widden, 1993); however, function-costing is an established method able to be used when trying to optimise the performance of one characteristic to another; i.e. best torque per unit mass, etc. There are many instances in engineering where one might wish to optimise a performance criteria per unit mass, cost, energy, etc. The use of indices explored here facilitates this within the framework proposed.

Work in other fields has taken performance indices and used this information *as an axis* (Ashby, 2005) as a means to, in essence, consider three criteria at once. This is not something that has been dealt with in this work; however, there is scope to build on this work to explore this in later work.

3.1.1.4. Boundaries of graphs developed and the information they represent

The *potential* expanse of relevant knowledge and information for graphical communication through the proposed method is vast. Application in this instance is reserved to consideration of motors, transmission systems, bearings, and brakes. This provides an ample platform on which to demonstrate the applicability and viability of the graphs developed. This will allow the approach to be applied and outcomes generated and analysed thereafter. This research will also consider only the criteria specified in appendix B.1.1. This is in order to maximise learning without focusing on criteria which will not provide best information on applicability of framework.

One of the main issues encountered in compilation surrounds availability of data. Many of the datasheets which were available on RS Components and other platforms utilised missed out key criteria such as mass, size, and issues were met with costs not being available without asking for specific quotes too on certain platforms. This has hindered conveyance of this information graphically; however, it is also clear that this information is not available to those using these platforms *now* to select components, which further emphasises the issue present.

3.2. Qualitative Information Databases

Another foremost point from the requirements list provided in section 2.6.2. after review of literature is a mechanism to provide comprehensive information on component types. Qualitative information is not something which can be communicated graphically or through *simple* drop down menus, but this information can still be immensely important, so a means of compiling this information is also required. As such, clear general information on each component type should be provided as a means to enable high-level interrogation of such information about component types; for instance, if a user wished to quickly review common use cases of a journal bearing this should be something which can be done easily.

From literature review, it is noted to have been specifically asserted that hierarchical categorisation of information in selection activities is crucial (Cebon & Ashby, 1997), and that this is corroborated in component selection specific research works (Zupan et al., 2002) (Poole & Booker, 2011). This is also something which cannot be delivered through the graphical means of communicating information, therefore it has been proposed that the taxonomy is developed to sit alongside the qualitative information databases. This facilitates interrogation of where a component type sits in the overall taxonomy, and also facilitates provision of the qualitative information necessary to inform decision-making.

Inspiration can be taken from other fields (biology) to assist in enabling the taxonomy and qualitative information to operate in tandem. Examples of instances from biology are given in figure 45 (Sources: https://www.onezoom.org/ and https://learn.genetics.utah.edu/content/evolution/tree/). In these examples, the user can explore "leaves" of the "tree" diagrams and review qualitative information presented. This may represent a solution to the presentation of qualitative information in future applications.

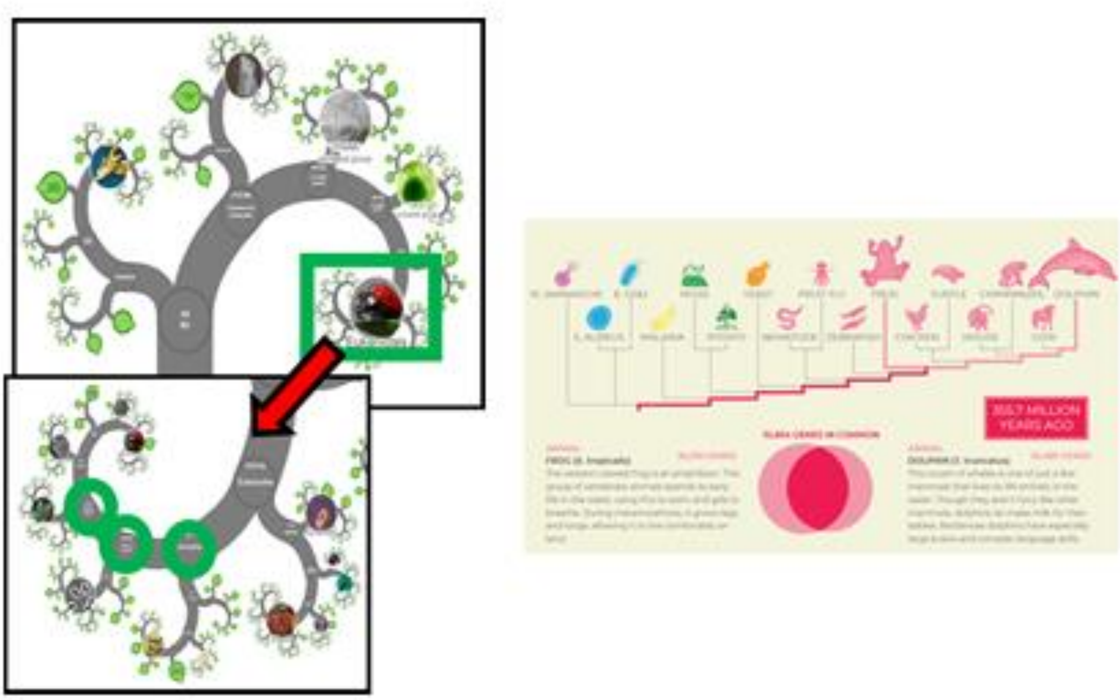

Figure 45: Example of hierarchical of structures used in biology to present relationships and to convey qualitative information.

Qualitative databases have been developed which promote consideration of solutions with which engineers may be unfamiliar, whilst also providing general relevant information for each component type. It is intended that this will assist in helping mitigate engineers using paradigmatic design tendencies or their own biases to justify design decisions. This is an issue which is encountered ubiquitously across a range of engineering disciplines (Ashby, 2005).

3.2.1. Taxonomy of Actuation Components

The first step in development of a structured model of actuation components was creation of a "broad" overview of methods for actuating within the use case of interest: rigid link robotic systems. This broad overview of components used in robotic systems is provided in figure 46 with an associated colour coding provided in table 5.

Table 5: Legend for Overview of generalised mechanisms for actuating robotic systems – corresponds to figure 46.

Technology Type	Colour
Pneumatically actuated	
Hydraulically actuated	
Motor actuated	
SMPs/SMAs	
Jamming Methods	

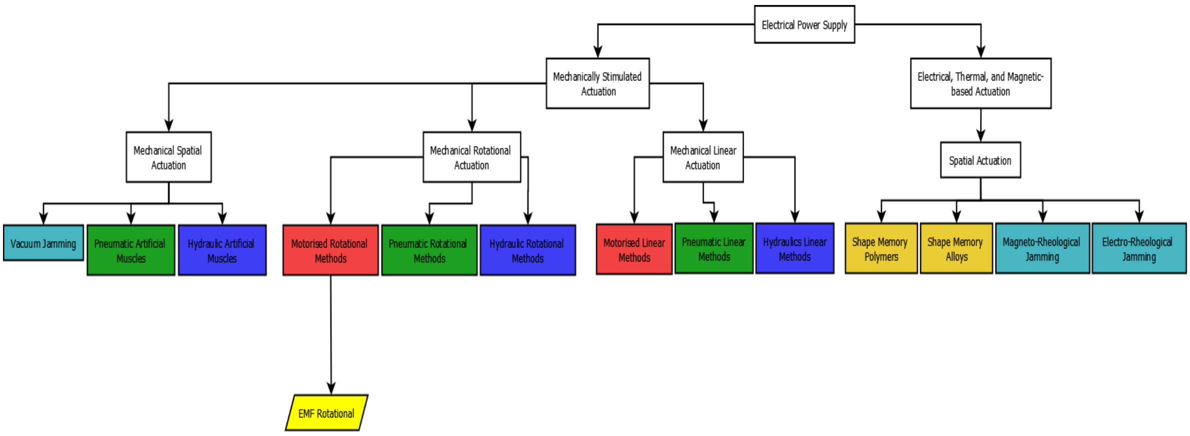

Figure 46: Overview of generalised mechanisms for actuating robotic systems

As per figure 46, the high-level taxonomy categorises and defines relationships by "family" and "class", as per table 2 (for better readability an enlarged version is found in appendix section B.3.). Omissions are made for the use of motors in pumps, etc. for pneumatics and hydraulics as this was considered to be excessive in detail without contributing to understanding *at this stage*. Also to be noted is the extension of electromagnetic force (EMF) to produce rotational motion. As a test case for this thesis, systems relying on this type of actuation will be the focus of the component selection task; i.e. the component selection exercise will not extend to hydraulics, pneumatics, etc. at this time, as inclusion would make an already vast task even more difficult to approach. An additional potential upside for formatting the taxonomy in the manner demonstrated is in support of categorisation of information into a future unified modelling language (UML) as discussed by other works (Nilsson et al., 2009) (Malec et al., 2007) (Prestes et al., 2013) (Schlenoff et al., 2012).

As a next step, relationships have been formed surrounding motors, transmission systems, bearings, brakes, and sensors. These component types have been deemed the most pertinent and relevant components, as per section 1.5. An example of the type of breakdown developed is given in figure 47, whilst the remaining hierarchical taxonomies are presented in appendix B.3.

3.2.2. Qualitative Databases

Examples of the qualititative overview across varying levels are presented, with the full breakdown available to review in appendix B.4. These overviews have been developed to represent proof of purpose for conveyance of qualitative information. Notice in figure 47 that some points are highlighted in a red box. This denotes the instances which are taken as examples of how qualitative information is initially proposed to be presented, and these examples are shown in tables, 6, 7, and 8.

Table 6: Offset axis motion transfer

Issue	**Details**
Maintenance	• Depends on material utilised
Performance	• Typically used in lower gear ratio set-ups • Good for transfer of motion, less commonly useful in high reduction/increase ratios
Typical Uses	• Instances where transfer is required between two shafts not in alignment • Often between two shafts not in axial alignment, but still parallel with X, Y, and/or Z offset

Table 7: Parallel shafts

Issue	**Details**
Maintenance	• Depends on method utilised. Some types (spur, bevel, etc.) can have issues with wear on gear surface, and wear of bearings.
Performance	• Vast performance range able to be attained – depends greatly on the specific component *type* utilised.
Typical Uses	• Useful in applications where co-axial transfer of motion is needed; • Useful for facilitating high accuracy, low noise, high efficiency, very large gear ratio range, and cost effective solutions also available
Notes	In literature, this type of motion transfer is known as parallel shaft motion transfer. It is suggested that co-axial motion transfer is a better term. As discussed in table 6, shafts can be parallel with an offset and be transferred to. Gear types falling under this heading require accurate alignment between the input shaft and the gearbox shaft, coaxially.

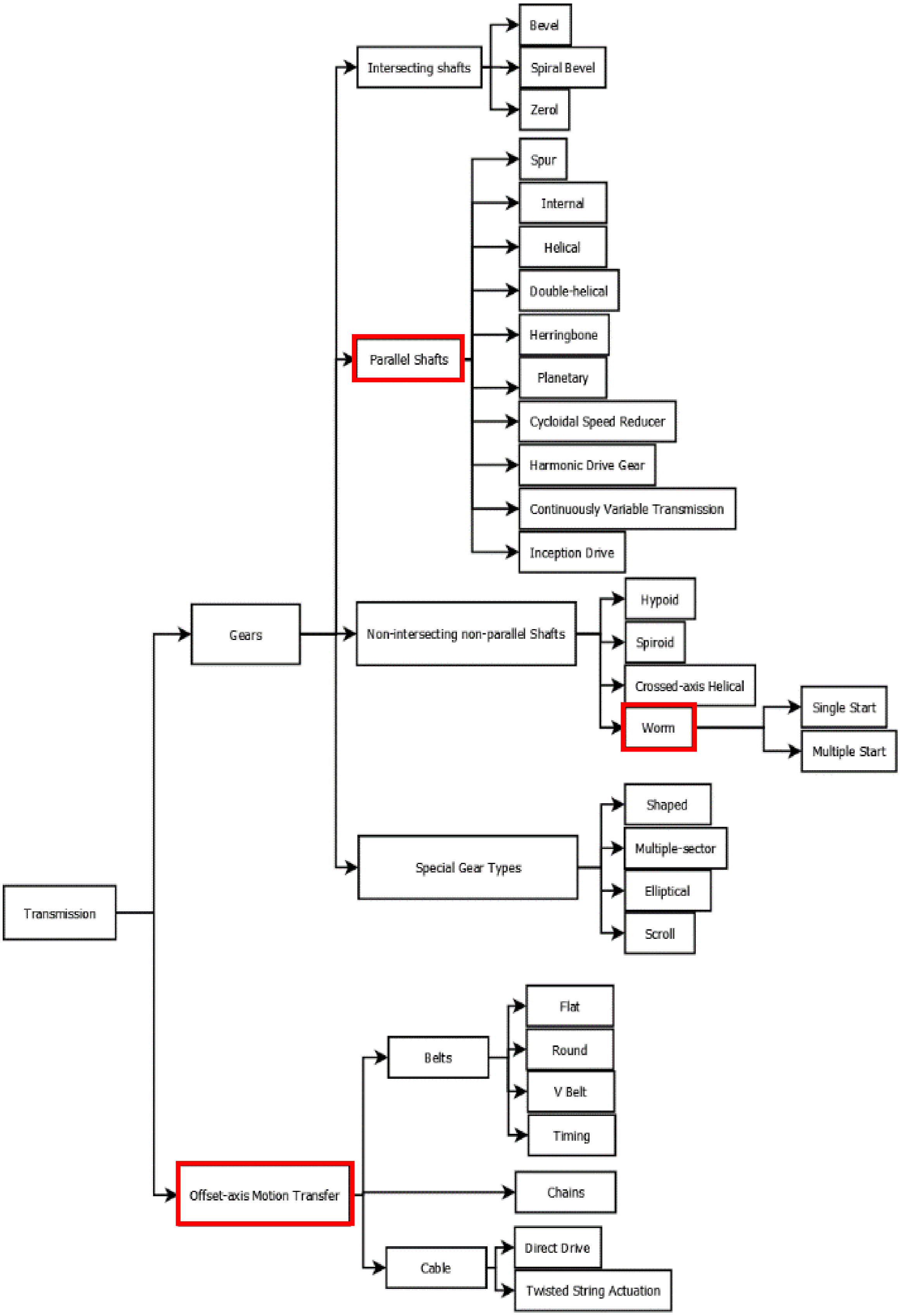

Figure 47: Taxonomy of transmissions used in mechatronic systems design. Items highlighted in red are explicated further in tables 6, 7, and 8.

Table 8: Worm gears

Issue	Details
Maintenance	• Worm shaft bearings can be subjected to large loads, potentially requiring replacement • Shaft bearings can be subjected to high radial loads, potentially necessitating replacement • Wear can increase backlash, potentially requiring other component replacement
Performance	• Non-backdrivable/self-locking in one direction, which can make for a good safety feature • Minimum backlash options available from some manufacturers • Typically low transmission efficiency • High friction losses due to constant sliding contact • Double enveloping solutions available, which support higher loads
Typical Uses	• Tend to be used in large speed reduction ratios

3.3. Guidelines to Support Component Selection Using Qualitative Information and Graphs

To clearly guide through the process, guidelines are created as a distillation of key tenets of other works coupled with the researcher's own experience. Two similar, but separate sets of guidelines have been developed which guide through different phases of an engineering design endeavour. The guidelines exist to promote a systematic approach to component selection, especially with reference to the component performance graphs. The negative effects of absence of methodical rigour have already been documented in literature review, but are surmised well as follows:

> *"It appears that problem solvers often start without a fixed plan in hope of immediately finding a solution from their knowledge bases without much effort. Only when this approach fails, or contradictions begin to emerge, do they adopt a more clearly planned or systematic sequence of thinking operations" (Page 48, Pahl & Beitz, 2007).*

Ashby and Hubka have also discussed how this "try and see" approach often ends with issues; there is no reason why component selection should be an exception. The problem, it is argued, is that in addition to comprehensive databases and methods for database interrogation, there exists no effective "systematic sequence of thinking operations" for component selection for the use case in mind, as has been demonstrated through review of solutions which already exist. Since this thesis proposes new methods to approach the component selection tasks, there also exists no guidelines for applying the tools developed in this thesis. Even so, engineers should be able to deviate from suggested paths where they see fit, which is why the proposed system only "guides" rather than instructs.

As previously discussed, there is guidance in textbooks which very generally guide component selection, but the detail is sparse. Additionally, no approaches have been encountered which deal with the relationships *between* component types. Furthermore, no approaches have been encountered which support implementation and decision-making at different **stages** of the design process. The guidelines developed in this work attempt to meet each of these challenges, whilst trying to leverage inventive ways of representing information in a structured manner not attempted previously.

The most seminal texts break down engineering design into 3 distinct stages; concept development, embodiment design, and detail design (Bietz, 2007) (Ulrich & Eppinger, 1994) (Stuart Pugh, 1990) (French, 1984). As such, the guidelines seek to support throughout, as applicable.

It is known that component selection is not something which is undertaken at a detailed design stage, as main function carriers such as components should already be defined during embodiment design (Gerhard Pahl et al., 2006). In the more particular context of mechatronic design, this is also corroborated by various V-models and other methodologies, as per section 2.1. As such, the supporting guidance for component selection provides clear approaches to support during concept-level development and embodiment-level design stages.

3.3.1. Points of the Concept-level Guidelines

Overview of the main points of the concept guidelines are given, as follows:

> **Step 1- Define Basic System Requirements**: Specifies the nature of information that the engineer should seek to compile prior to selection process.
>
> **Step 2 - Approximate System Requirements**: Based on the previous task, *approximate* (at this stage) results of the required performance of the system will be developed. This enables tangible information on the components to be sought to be realised.

As discussed in section 2.2., there is clear consensus in engineering design and in analogous selection processes that definition of requirements must take place in the first instance (Ashby, 2005) (Cebon & Ashby, 1997; Harmer et al., 1998). As such, steps 1 and 2 support definition of *overall* system requirements before converting to requirements which are more tailored towards what the *actuator* system must achieve.

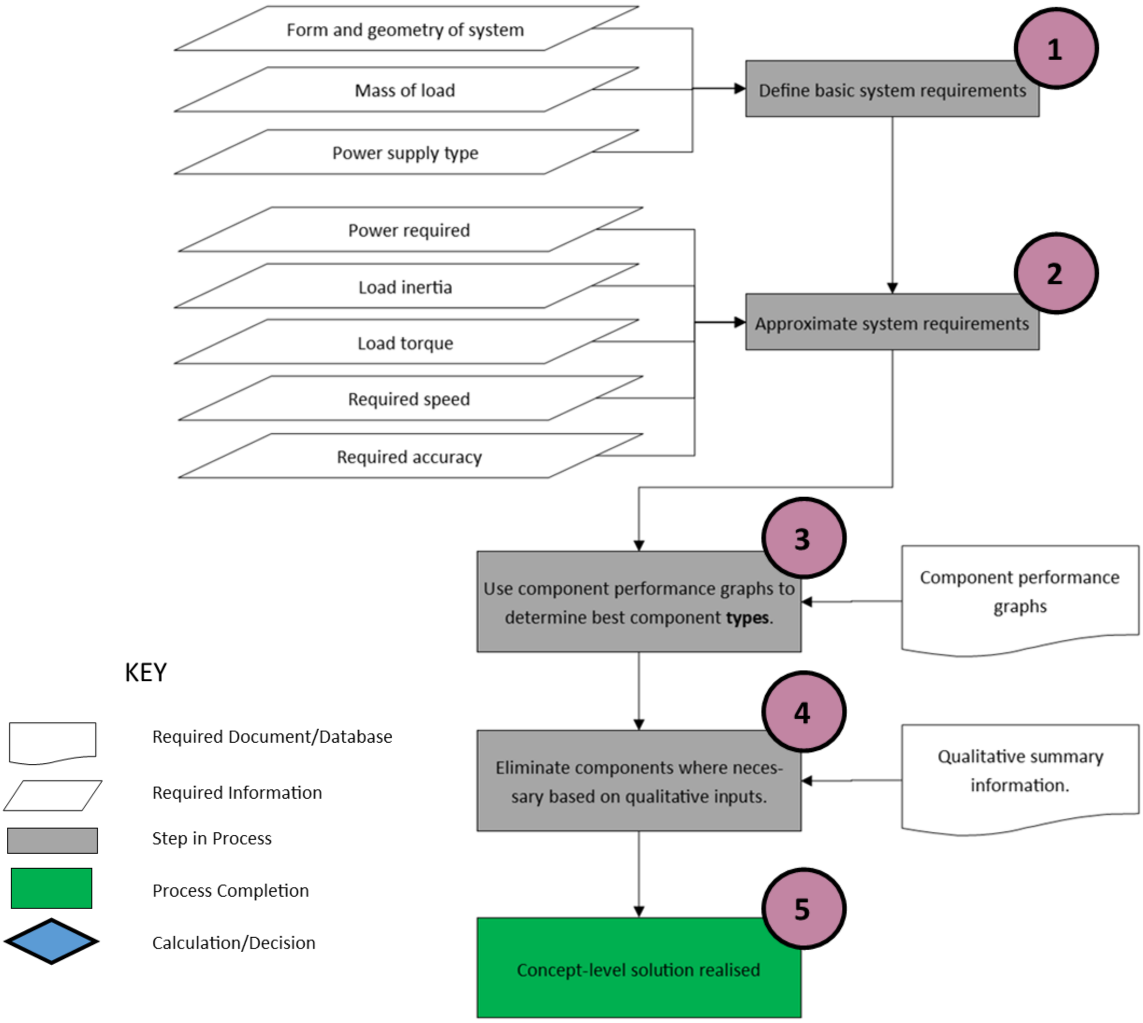

Figure 48: Initial Concept Level Component Selection Guidelines. Steps denoted in top right

Step 3 - Use Component Performance Graphs: Utilise the performance graphs in order to identify the best *types* of components. This will provide understanding of the type of components which should be considered in greater detail later based on quantitative performance, and will provide rough figures which can be leant on to further develop.

Whilst existing mechatronics methodologies make allusions to the use of non-specific "component databases" (Zante & Yan, 2010) (Melville, 2014) (Iris Graessler & Hentze, 2020), step 3 specifically prescribes the use of component selection graphs as a platform to be interrogated to enable identification of quantitatively capable solutions. Similarly, step 4 prescribes consideration of the qualitative information which may be influential in dictating the choice of component made.

Step 4 - Eliminate Components Based on Qualitative Information: Using the qualitative inputs, the engineer should eliminate options which are quantitatively capable, but may struggle for other reasons; inability to deal with environment, for example.

Step 5 - Concept-level Solution Realised: At this stage, a concept solution for component selection should be in place with a range of component options available to be considered in this concept-level solution.

3.3.2. Points of the Embodiment-level Guidelines

At this stage of development, the process of applying embodiment guidelines follows a similar structure as in concept-level application. The main differentiating factor is that embodiment level is required to be far more precise.

Step 1 – Determine priority of criteria importance: As embodiment guidelines support the user in reaching an individual component, the first step dictates that the user should utilise the Analytic Hierarchy Process (AHP) to determine the criteria which are most important in any components to be selected.

Full and extensive justification on the choice of AHP as a decision-making method is provided in appendix B.5. Rationale for significance of decision-making in component selection is covered in section 2.5.3.

Step 2 - Refine System Requirements: The user must develop knowledge of the system requirements needed to select components. In the context of the user case considered in this thesis, suggestion has been made about the type of information likely to be needed; however, the user should also make their own judgement as to what criteria to include and omit from consideration.

Step 3 - Calculate Required Performance: The user should calculate the required performance of the actuator system, based on the previous inputs derived from the overall system requirements. Again, the user should omit and include as necessary, but suggestions have been made to assist this process.

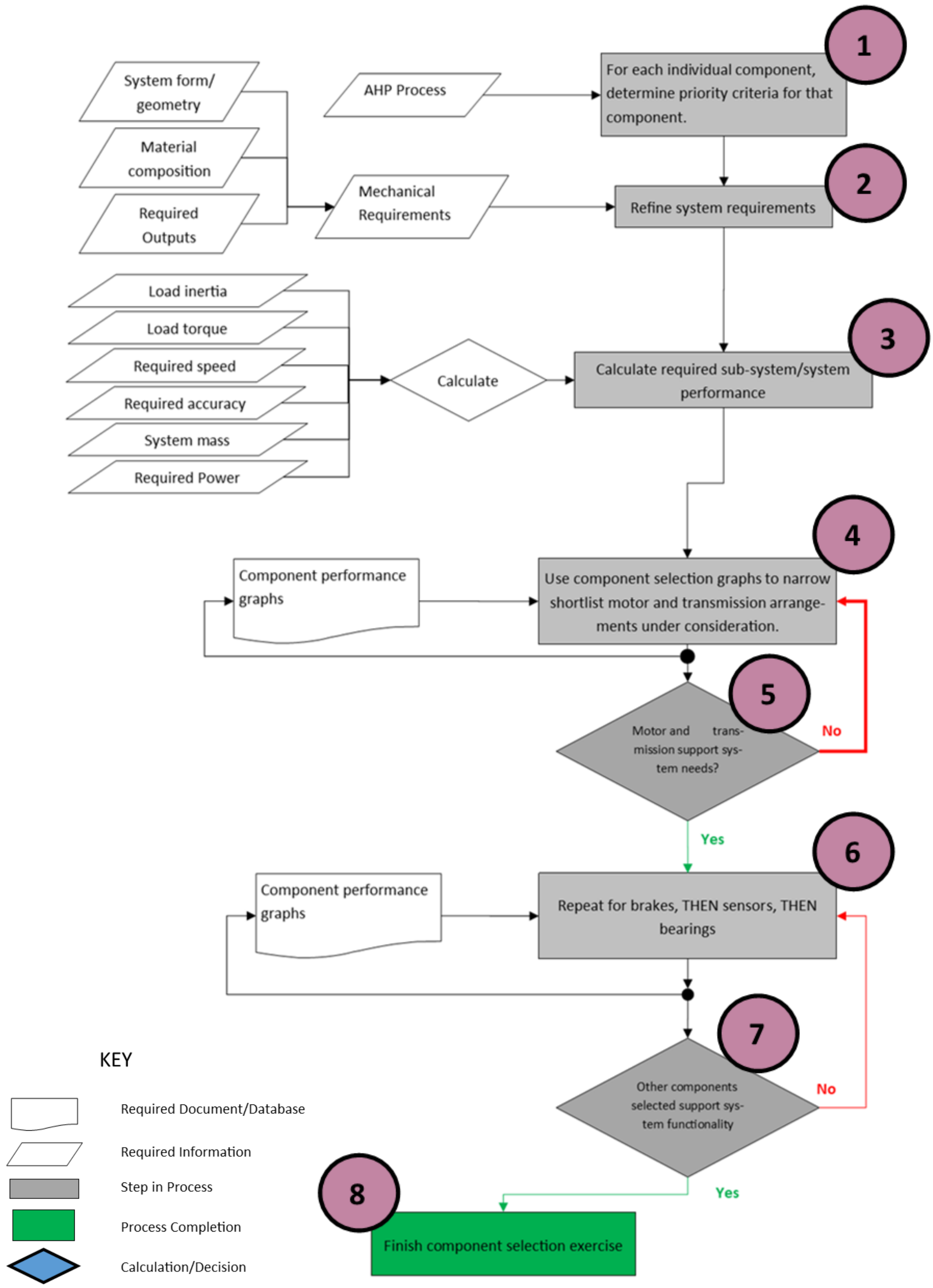

Figure 49: Initial Embodiment Guidelines.

Similar to concept-level counterparts, steps 2 and 3 of embodiment-level component selection are based on the clear need to define the requirements that the selected components must meet in order to enable the overall system to function as required. The *actuator* requirements are drawn directly from any *overall* system requirements, before being converted into requirements as they relate to the component selection which must take place.

Step 4 - Use Component Selection Graphs: Component selection should be completed for motor and transmission systems, as these are the primary drivers of the system. These need to be in place for a system to function, whereas other criteria generally supplement this functionality.

Step 5 - Check for Suitability: Verify correctness and iterate as necessary.

Step 6 - Repeat Use of Component Selection Graphs: Utilise graphs to select remaining components.

Step 7 - Check for Suitability: Verify correctness and iterate as necessary.

Also similar to concept-level guidance, steps 4 – 7 endorse leaning on the tools developed in this project as a means to interrogate relevant information. The interrogation at this stage is based on more clearly required inputs from requirements definition, and also supports a more refined application of the selection graphs such that individual instances of components can be chosen.

Step 8 - Embodiment-level Solution Realised: At this stage, the user should have specified a complete list of components to be utilised enabling integration into the solution.

3.4. Framework Functionality

With reference to table 9, it has been delineated what this approach seeks to address. In order for the *whole* solution to function, the interdependent elements must work together. The preceding sections have introduced several separate tools; however, the overall intention is that these separate tools (or methods) should function in unison to achieve the desired end of assisting in the process of selection of components. In order that these tools can be applied in a robust fashion, their interdependencies are formalised through an over-arching framework to guide the process of component selection. Figure 50 outlines the architecture of the component selection framework proposed to support all novel aspects of this work operating in concert towards delivery of solutions.

The guidelines encourage the user to consider certain key parameters, to engage with the qualitative taxonomy, and to leverage the component selection graphs as required. The sample database is not utilised directly by users, but is key in underpinning the function of the graphs. In summary, the user should primarily be concerned with utilising the guidelines and lean on other methods as advised by the guidelines, though it is acknowledged that there should be flexibility in allowing engineers to be reflexive depending on their own requirements. The framework is labelled with “steps” which are to be taken in applying the framework, as shown in in figure 50. As per other works which have taken a similar approach (Francalanza et al., 2017) (Borg, 1999), this is known to support clear navigation of the framework in implementation of the other methods proposed in this work.

3.4.1. Overview of Framework Application

The framework provides overview of how the discrete elements of the framework relate to one another, whilst accompanying numbers describe the order in which elements of the framework should be consulted. The order in which these should be consulted and the nature of the operations is described as followed, with each number referring to the corresponding step number from figure 50.

Step 1: Component selection is an activity within an overall system design process. The overall system should have a design specification which outlines the requirements of the system. Relative to the *overall* system’s performance requirements, step 1 requires that the actuator’s requirements are defined such that specification of suitable components is based on the specific requirements of the actuator. For example, a manipulator’s overall requirement may be to manoeuvre a 1 kg load; however, the actuator’s at the base of the manipulator must manoeuvre the 1 kg load **and** the mass of all other components, linkages, etc. in the manipulator. Therefore its requirements differ from the overall system requirements.

Step 2: Having defined the sub-system requirements, users are encouraged to interrogate the concept-level design guidance. This guidance supports the user in consideration of the correct information at the right time and supports reference to relevant tools which aid the engineer in actuator design and component selection.

Step 3: As per the guidance offered in step 2, engineers should interrogate broad qualitative information on component types as a means to identify qualitative traits of components which may inhibit them from performing as needed.

Step 4: Following omission of component types based on qualitative information, candidate solutions should next be interrogated on the basis of their ability to perform quantitatively. The solution proposed in this work to aid this involves the use of component performance graphs, to represent the performance ranges of components available from manufacturers and suppliers. After interrogation of this information at component level, the user should have a shortlist of some of the most appropriate solutions likely to be capable of enabling the system to perform.

Step 5: The user should return to reference a new set of guidelines as the design advances, referencing embodiment guidelines, which support reaching a specific solution which should be implemented in the manufactured system. Guidance at this level is targeted in more detail, and again defers the user to consult other tools at the appropriate point to maximise effectiveness.

Step 6: With more clearly defined requirements of the system, the user is encouraged to consult qualitative information in more detail, paying particular attention to qualitative information pertinent to previously shortlisted solutions. Qualitative review at this stage should allow more refined removal of any shortlisted components based on qualitative issues raised.

Table 9: Necessary Aspects of Component Selection Solution Proposed.

Aspect	**Value/Utility**
Hierarchical Taxonomy and Qualitative Information Database	Categorises a range of actuation components and defines their relationships in order to understand the links between each. Acts as a platform to convey qualitative information on component types and to provide overview of available solutions, seeking to address points 2, 3, (a), and (f) from page 38.
Sample Database	Provides a resource from which component selection guidelines and (to a lesser extent) the qualitative model can be developed.
Component Performance Graphs	Represents component performance utilising graphs in a manner not encountered previously in literature, with the aim of enabling intuitive comparison of quantitative aspects of component performance data. Tries to address issues outlined on page 59, and virtually all of points 1-3 and (a) – (f) from page 38.
Selection Guidelines	A process flow to guide selection of appropriate components for use in actuators for robotic systems.
System Requirements	Finally, external information is brought into the process to inform the elements previously mentioned and to maximise the effectiveness of their use.

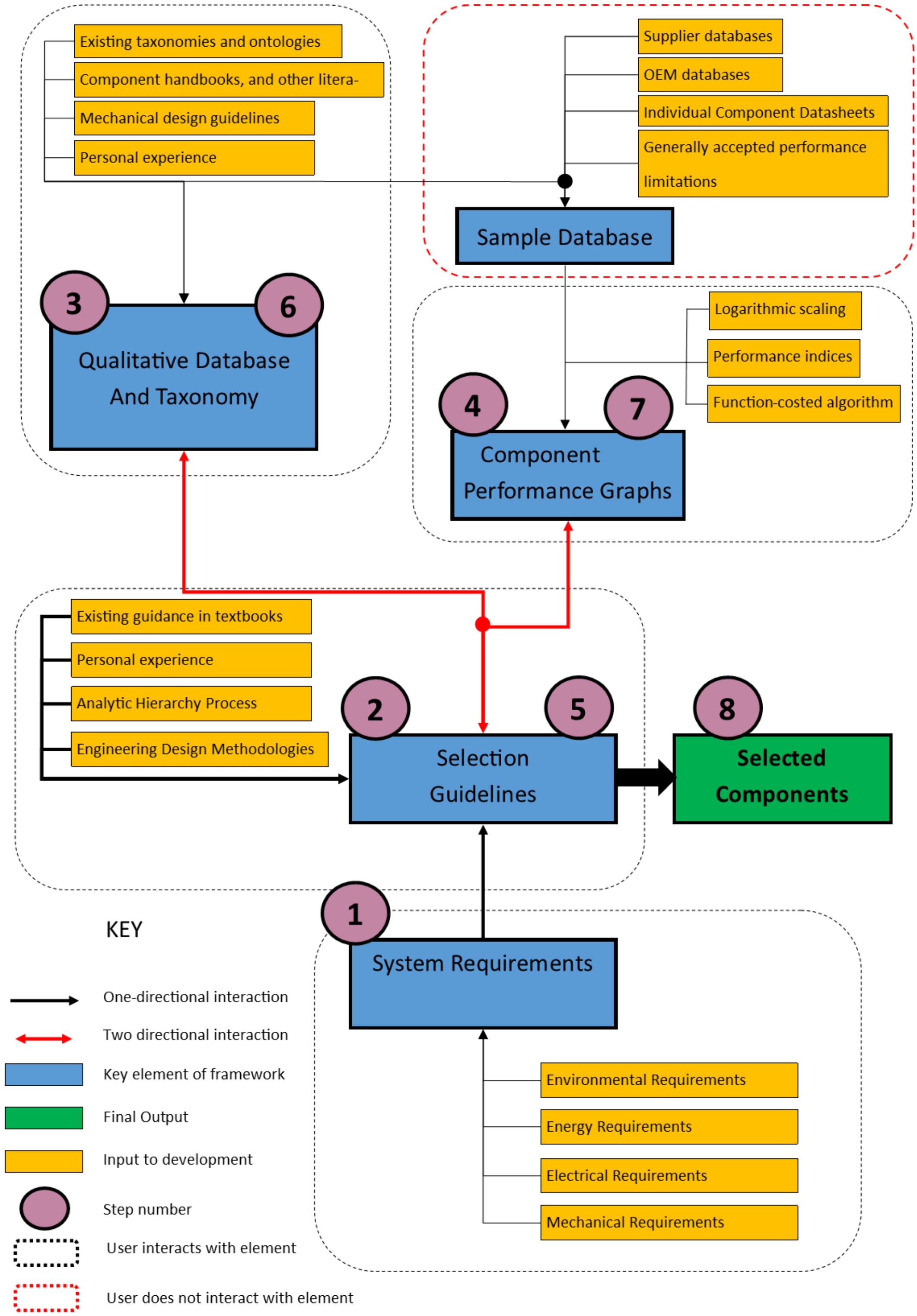

Figure 50: Relationship between elements of component selection framework. Red lines indicate two-way passage of information. Red boxes indicate information informing two other areas.

Step 7: With a clear understanding that all solutions remaining are qualitatively capable of realising a functional solution, graphical representations should be interrogated to define a specific component type(s) for consideration. Upon definition of specific component types to consider, the graphical interface should be interrogated further to review specific component *instances* in order that specific solutions to component selection can be selected.

Step 8: Guidelines at embodiment level have supported iteration through remaining processes. Upon completion of embodiment guidance, the user arrives at selected components.

3.5. Findings from Compilation

Below, some of the findings from compiling the framework are surmised.

- Datasheets across manufacturers are poorly standardized, which increases difficulty in quickly attaining the desired information. This aligns with similar findings from many years previous (Vogwell & Culley, 1991) (Harmer et al., 1998), which suggests that the issue is still poorly addressed in commercial and academic solutions. The proposed framework leveraging a graphical representation of quantitative information could be extremely helpful in navigating this issue in an intuitive manner;
- A wealth of knowledge has been generated about the effects of indices when considering different component types **and** across different criteria; using indices for selection works differently depending on the requirement, criteria, and component type. Knowing how to use these indices does require a certain amount of prerequisite *basic* engineering knowledge. This is helpful in potentially *reducing* the amount of expertise required; and,
- It has been necessary to ascertain a range of knowledge regarding how to structure guidelines, how to categorise relevant information, how to represent graphical information effectively, and how the elements of these discrete methods should be deployed in an over-arching framework to effectively guide their use in an effective manner. This has been an extremely extensive undertaking from which a wealth of understanding has been developed.

3.6. Enabling Development by Other Interested Parties

In future applications, it is expected that the framework structure should remain unaltered, therefore the framework should be something which can be referenced across application in many different applications without any real need from suppliers or OEMs to adjust this aspect of the work. The methods used in the implementation of the framework, however, may require tailored development depending on the application, discussed as follows.

3.6.1. Component Performance Graphs

Any party interested in representing component performance information graphically should be able to follow the guidance outlined throughout section 3.1. In the example of a supplier or OEM, a database of components and their criteria is presumably already easily accessible, which is a useful prerequisite. This should allow many of the issues encountered in section 3.1.1.1. of this work to be circumvented for OEMs and suppliers. Assuming that the same component types are to be represented, the approach presented in section 3.1.1.2. can be relied upon, where the first criteria is plotted along the X-axis, whilst the second criteria should be plotted on the Y-axis as it varies with respect to the X value. Virtually any quantitative information should be able to be represented in this way using the approach developed and a logarithmic scale. Utilisation of information developed in this thesis around performance indices (section 3.1.1.3.) should also be transferrable with little effort from suppliers or OEMs.

3.6.2. Qualitative Databases

Much the same as graphical conveyance of information, the qualitative databases proposed in this work should be used and compiled in the same manner as they have been in this work. In compiling qualitative databases it has been found that this can only be achieved through extensive reading and understanding of the relevant quantitative information before presenting this in a more intuitive and easily reviewed format, as proposed.

Whilst this task needed by undertaken for the components covered in this thesis, any efforts to supplement the work of this thesis will require additional effort on the part of the OEM, supplier, or researcher interested in making the database more comprehensive. In establishing databases for different component types, it is considered that extensive research or the services of at least one expert will be required to assist in populating additional databases.

3.6.3. Step-based Guidelines

In utilisation of guidelines, OEMs and suppliers should be able to rely on the guidelines already proposed as a means to support selection of the component types considered in this document. In adding more components or in applying this approach to the selection of a different group of components, it is considered that tailored guidelines may need to be created. The structure proposed by the guidelines should be a strong template to be used in any efforts of this nature, and it is advised that key steps promoting derivation of selection requirements from the overall system requirements and the use of AHP to provide precedence are retained.

In guidelines supporting selection of components not considered in this work, it is expected that there may be need to iterate and refine this process in order to ensure that nuanced elements of the selection and design process are captured. This has been necessary in the study conducted and has enabled a refined set of guidelines to be produced, strengthened through extensive testing across development of 7 actuators.

4.0. Validation Case Studies

4.1. Case Study 1 – Joint Actuator Design for a Robot Arm

Case study 1 will use the framework to develop a new actuation solution for the Agribot arm, figure 51. This will entail application of the guidelines in the development of each joint and will allow assessment regarding the efficacy of the framework. The main objective in design of this system is mass reduction. In line with Yin's recommendations on case study research, the researcher will put himself in a position as close to that of the actual project as is possible.

A brief introduction to the arm developed and some of the generic requirements of this are provided in appendix C.1.

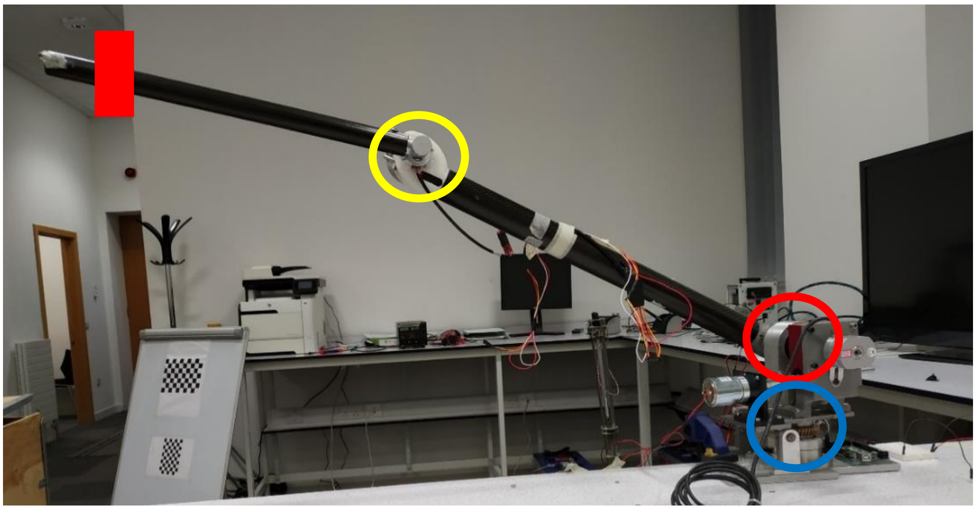

Figure 51: Joints in the Agribot Arm. Joint 3 (yellow), joint 2 (red), and joint 1 (blue). Red box highlights where joint 4 **was** positioned in early designs.

4.1.1. Concept Level Component Selection

The framework is first applied to a concept-level selection process. This process will iteratively complete component selection for each joint up to a concept level, beginning with definition of system requirements, as per the framework's concept-level guidelines.

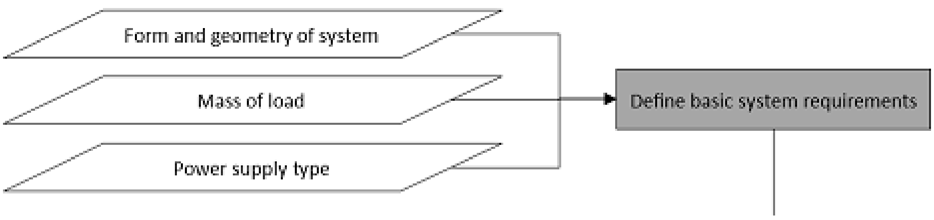

Figure 52: First step of concept-level application.

4.1.1.1. Identification of Candidate Components for Joint 4

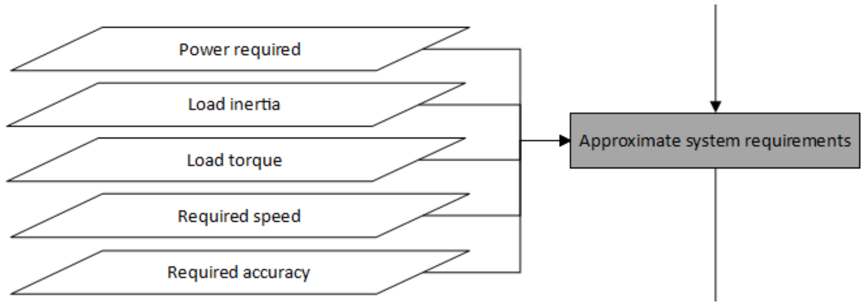

Figure 53: Definition of actuator requirements (approx.), as per the guidance of the guidelines.

The requirements for joint 4's performance are defined as per the guidelines, and are presented in table 10, below:

Table 10: Performance requirements of joint 4's actuator.

Criteria	Value
Power	0.36 W
Inertia	0.0103 kg m^2
Torque	1.034 Nm
Required Speed	~ 20° per second

Using a graphical approach, the possible mechanisms through which this can be approached can now be considered. Since approximations have been made in the approach to calculations thus far, there is a need to consider components with performance which is also **approximate** to the values calculated thus far.

4.1.2.2. Concept-level Motor Selection for Joint 4

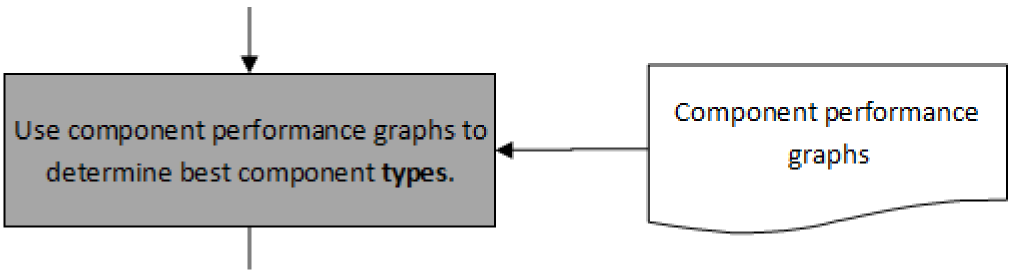

Figure 54: Guidelines prompting for the use of graphs.

Being that the torque represented on the graph is the maximum continuous torque, it is correct to say that all motors to the right of the **green line** in figure 55 should be able to provide adequate torque to perform the task as required in **direct drive**. Those to the left of the green line will struggle or fail to provide the torque required *without sufficient gearing*. This is an important observation, underpinning the effective use of this approach to select actuation components. It is observed that guidance on using the graphs would enable better use, therefore this is addressed in appendix D.1.

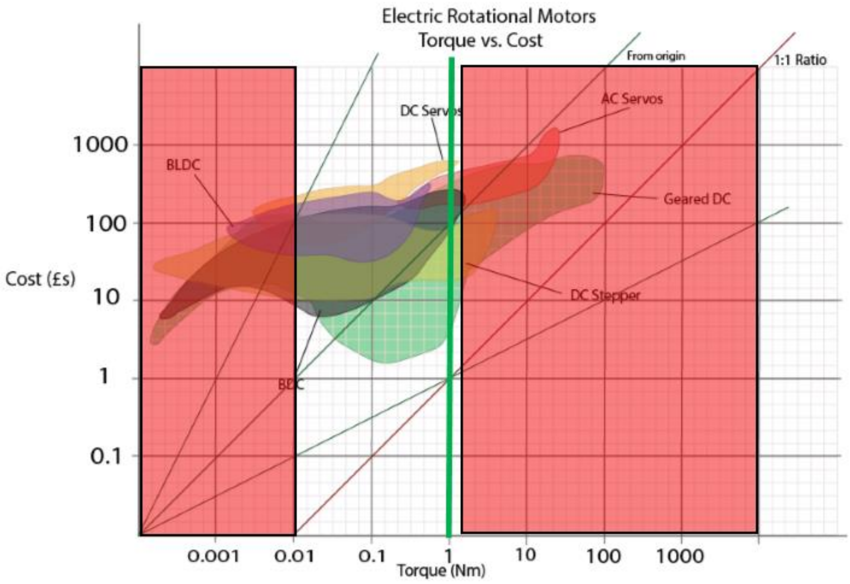

Figure 55: Approximating performance required of robot joint 4 motors.

The green line represents the required torque therefore a large contingent of the components represented should be omitted, as per red boxed region. Motors still under consideration have torque up to slightly greater than needed performance to be considered and motors with up to 2 orders of magnitude *less* than is required. This allows consideration of the most appropriate gear ratios.

The use of graphs has rapidly allowed intuitive assessment of component types available, and definition that some mid-range DC stepper motors and brushed DC motors could be utilised, whilst some lower midrange BLDC and geared DC motors could also be used. Using existing approaches, this general overview would have required extensive experience or reasonable research to attain.

4.1.2.3. Concept-level Transmission Selection for Joint 4

With transmission, all components **left** of the plotted line are not useful, as they lack sufficient torque limits; there is a definite lower limit to this criteria, below which the system will fail. This necessitates a different use of graphs employed in selection of transmissions. The graphical method has again allowed the engineer to intuit and understand the ranges of components to consider.

Definition of an initial range in which components can operate facilitates iteration taking place to determine an appropriate gear ratio for the system before shortlisting of suitable components. The transmission must facilitate the torque and speed needs of the system. Maximum speed and torque are criteria which are represented in graphs, so are demonstrated to be successfully interrogated using a graphical method in order to shortlist appropriate component types.

4.1.3. Concept-level Graph Interrogation: Conclusion

The preceding sections have outlined the concept-level solutions that are to be put forward. Table 11, below, summarises candidate solutions attained to avoid repetitious information being presented.

Table 11: Summary of potential components for joint 4.

Component Type	**Primary Candidate Components**	**Secondary Candidate Components**
Motor	BDC, BLDC, stepper, or geared DC	DC servo
Transmission	Planetary gearbox or Harmonic Drive Gears	Worm gear or cycloid gears
Bearings	Roller bearings, plain bearings, or ball bearings.	*Not applicable*
Brakes	*Not applicable*	*Not applicable*

4.1.3.1. Utilising Qualitative Information in Order to Assess Qualitative Performance of Candidate Components

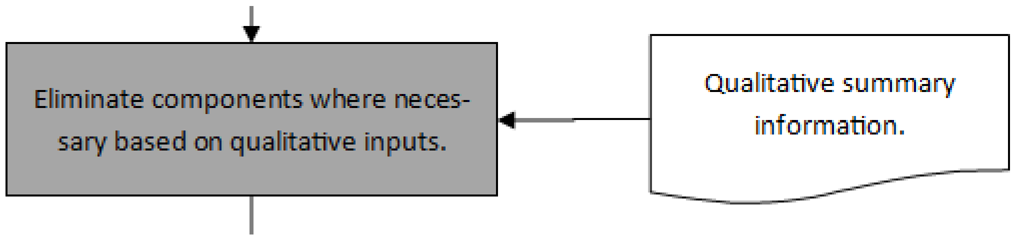

Figure 56: Utilisation of qualitative inputs in order to define best component types for consideration.

The framework also outlines qualitative review as a means to assess component validity, and this is assessed in this section at concept-level. These inputs are demonstrated to ensure that awareness of potential issues is raised at an early stage in concept-level development.

Table 12: Qualitative issues raised with motors.

Motor type	**Potential Issues**
BLDC	Issues with brush replacement, could be issues requiring maintenance. Frequency depends on the brush material, running speed, etc.
BDC	No issues raised
Stepper	Potential positive of not needing sensors – open loop control may be sufficient for task in hand Potential noise issues with some models Potential issues with missed "steps" (i.e. accuracy errors) if load torque is too high on motor

Geared DC	Potential for inefficiencies depending on gearing used in motor Gear type used can raise maintenance issues over time – again, dependent on implementation and gear material, etc.

As shown in table 12, potential issues to be aware of have been brought to the engineer's attention surrounding potential motors. The same process is able to be replicated without issue for other component types, enabling cognizance of a range of issues from an early stage. With traditional methods employed in component selection, this is reliant on an engineer's expertise (which is subject to bias), or requires research into specific components to raise awareness of potential problems.

4.1.4. Embodiment Application

Embodiment guidelines are outlined as a part of the framework, as per section 3.3.2.

4.1.4.1. AHP Process

The first step defined by the guidelines is to establish the most crucial criteria for each component. The whole process is available to review in appendix C.2.1.; however, as an example, motors are documented, as follows:

Table 13: Priority for consideration of motors.

Criteria	Weight	Priority
Torque	33%	1
Speed	14%	3
Cost	8%	5
Mass	10%	4
Stall Torque	28%	2
Power	5%	6
Voltage	2%	7

4.1.4.2. Refine System Requirements and Calculate Performance Needed

As per the guidelines, key performance required from joint 3 is delineated in table 14, below:

Table 14: Definition of requirements needed from actuator to allow system and sub-system to perform as needed.

Criteria	Value
Reach	1.0 m
Load mass	0.063 kg
Equivalent load mass including	0.15 kg
Approximate power required by	0.661 W
Inertia of arm about joint 3	0.067 kg m^2
Load torque (including FoS)	1.261 Nm
Required Speed	30°/s

4.1.4.3. Motor and Transmission Selection in Joint 3

Having determined key requirements for the joint and criteria precedence, further application of the framework facilitates definition of the key actions required to define solutions. In use of graphs, it is recommended that the top two criteria from the AHP process are initially relied upon as the criteria used to facilitate definition of appropriate solutions.

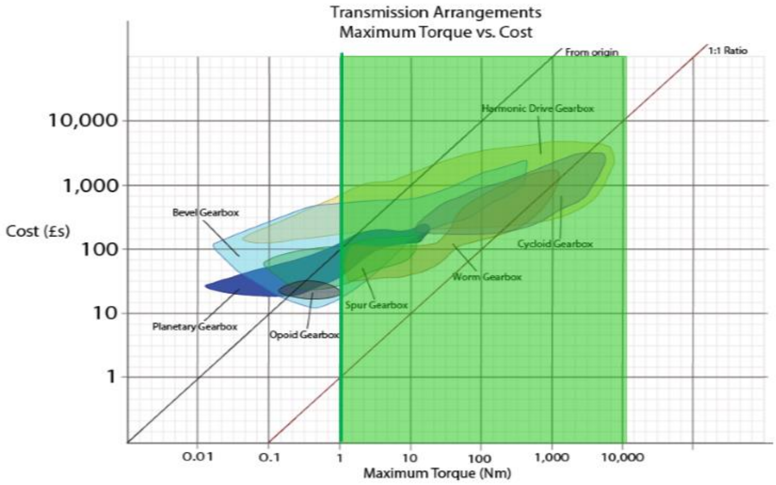

Figure 57: Initial search for a capable transmission system.

The inputs from AHP becomes very useful at this point. Using this information, the gear ratio can be adjusted, as long as the speed and the torque output of the arrangement will facilitate the movement of the arm as required.

Consideration of viable gear ratios has next taken place, culminating in definition of a gearbox with ratio 60:1. As such, a motor will be required to provide at least 0.0188 Nm at an input speed of at least 300 RPM to enable the system's correct function. Graphs are demonstrated to have been useful in reassessing options available given these change in requirements for this component type. This further demonstrates that the graphical tool has been useful in being adaptive to the changing nature of engineering design tasks.

The green boxed region in figure 58 highlights solutions which are useful in meeting joint 3's motor requirements at the gear ratio considered. The green box is narrower than at concept level, due to more accurate figures and a more refined process.

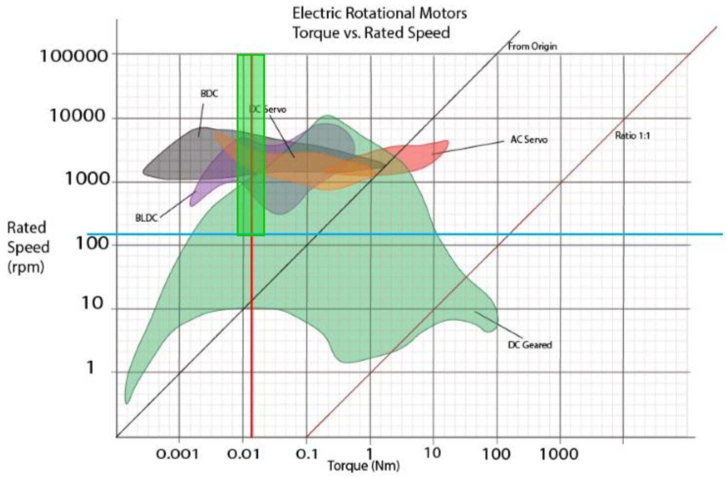

Figure 58: Motor speed and torque requirements for joint 3 transmitted through 60:1 gearbox.

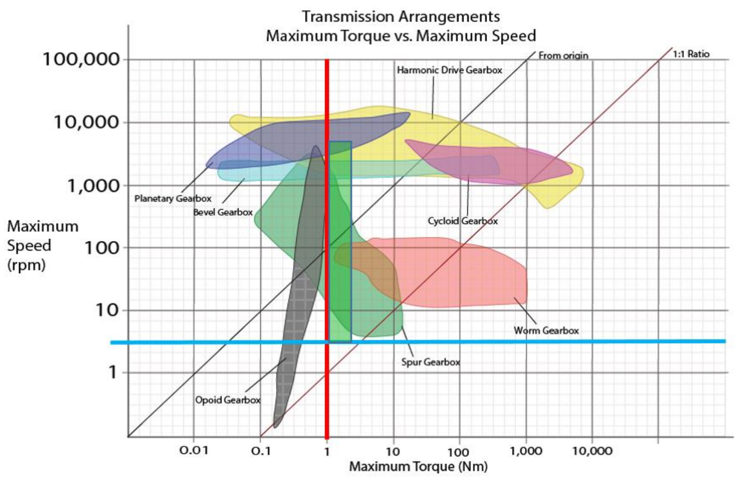

Figure 59: Maximum Torque v Speed for transmission selection.

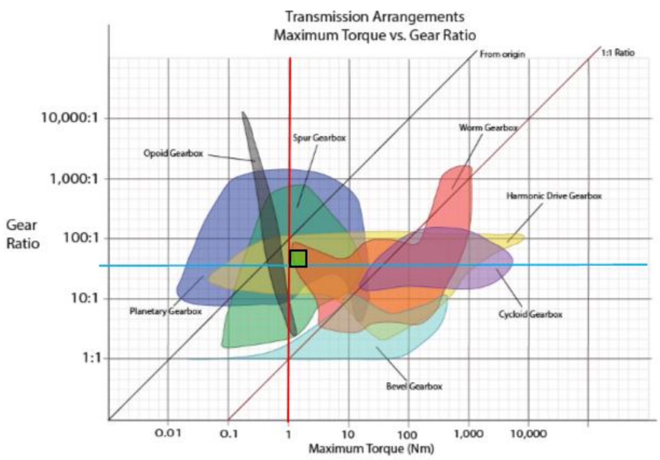

Figure 60: Transmission torque rating against gear ratio. Ideal solution located as highlighted, suggesting HD, spur, planetary, and worm solutions are liable to be a good fit.

With refined considerations, it can be seen that BDC, BLDC, DC servo, and geared DC present acceptable solutions. This shortlist is akin to our concept level shortlist already developed, but the considered region is less divergent than in the concept selection due to the refinement of the figures used. A slight margin is included to allow a broader range of components to be considered. It can be seen from figures 59 and 60 that planetary gearboxes, Harmonic Drive gearboxes, worm gearboxes, or spur gearboxes may be of utility. The gear ratios of these gearboxes are considered in order to ascertain whether solutions provide the approximately 60:1 ratio needed.

If a ~60:1 ratio is to be applied, bevel gears cannot be considered. They do not provide a 60:1 ratio, therefore it is not capable of performing. As per AHP, gear ratio is a lower priority parameter, so can be adjusted more readily than key criteria.

Before choosing a specific component, component types are reduced as far as possible, allowing those with the greatest potential to be considered closely. Quantitative and qualitative criteria are considered in order to remove motor types which are least valid. Figures have shown graphs allowing consideration of the required nominal torque across a range of criteria. This allows rapid and intuitive understanding of how a component's criteria relate to one another, and where the best solutions likely lie.

4.1.4.4. Qualitative Overview

From prior quantitative review, DC servo, geared DC, and stepper solutions are noted to be most suitable for joint 3's requirements. Review of qualitative database yields the following assertions:

1. DC servo motors can only sense **their** output. They cannot account for inefficiencies and backlash after running the output through gearboxes.; and,
2. BLDC motors are best used in high speed applications.

Information tables have been referenced to assist this process, as in appendix B.4.

An informed decision to remove all motors from consideration except for geared DC motors in the 0.01 Nm torque range has been facilitated by the framework.

Having utilised graphical methods and qualitative overview methods to define a component type, a geared DC motor is to be interrogated further. Specific instances can next be compared utilising a graphical approach. Comparison of individual components next takes place, where previously defined AHP precedence is again relied upon to guide the comparisons

4.1.4.5. Selection of a specific component instance

At the outset of selection of a specific component being selected, some interesting issues were encountered which raised some learning opportunities surrounding possible features future iterations of the graphs should have. This is discussed further in section 5.5.1. of discussion, and is covered in appendix C.3.

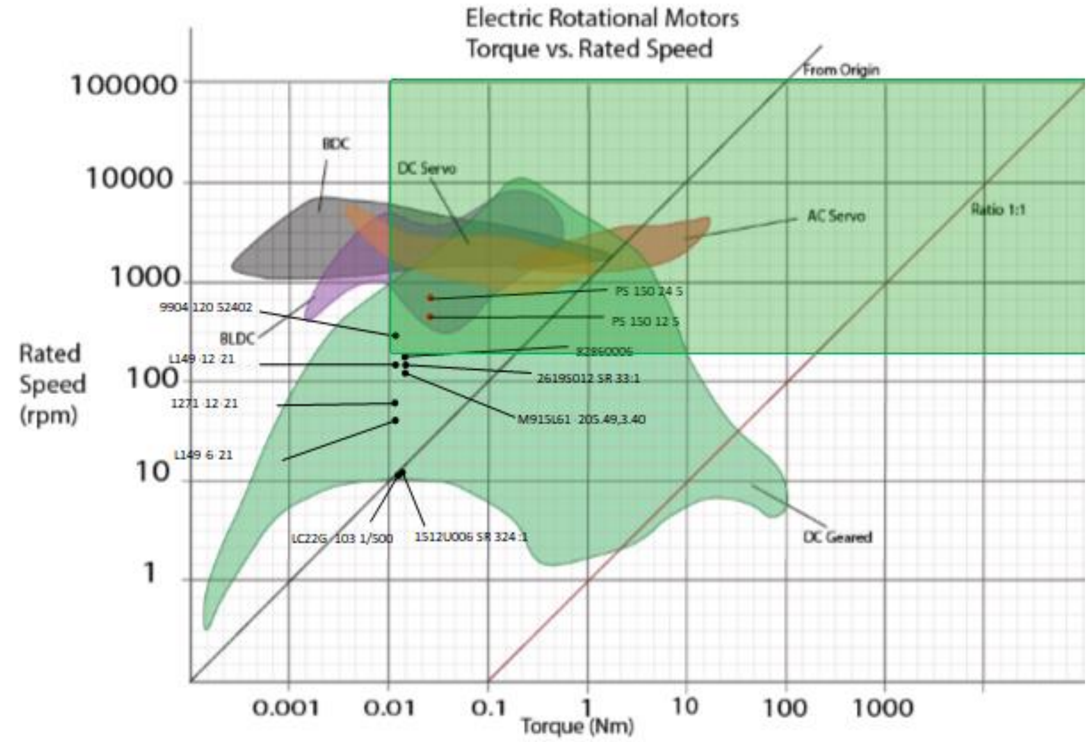

Figure 61: Comparison of motors.

Figure 61 constitutes the first use of the graphical method as a means to compare individual components, as opposed to component *types* demonstrated to have been compared previously. Further assessment utilising this approach can also be supported, again with reliance upon the order of precedence defined by the use of AHP earlier in the sequence of operations suggested by the guidelines.

As per appendix C.2.1., comparison based on AHP has taken place, and has supported effective comparison. The Micro Motors PS-150-12-5 is shown to provide a lightweight, cost-effective, and power-efficient solution as per the graphs. This motor is not the outright lightest, but is negligibly heavier than the 9904-120-52602 and provides a significantly better outright and function-costed power density. Indexing for power density has also been assessed as a supplementary consideration to support selection, enabling successful cross-reference on this basis.

Comparison of the motors in table 15 demonstrate that the approach taken is capable of selecting components arrangements which compare favourably with a prior selected components. The motor selected using an *ad hoc* approach based on knowledge of existing guidelines has returned a motor which performs well, but is 4x more expensive, more than twice as heavy, and consumes ~9x as much power, while requiring a larger voltage supply. It provides more speed and torque than the motor selected, but is vastly over-specified for the task.

This study is the first iteration of this work. It has provided a solution which conforms better to the requirements of the system; however, system testing is still necessary - it does not matter if it is lighter or cheaper if it does not work.

Table 15: Comparison of motor selected versus the motor utilised originally.

Criteria	**Maxon RE 35**	**Micro Motors PS 150 12 5**
Torque	0.101 Nm	0.05 Nm
Cost	£239	£60
Mass	0.340 kg	0.15 kg
Voltage	24 V	12 V
Power	90 W	11 W
Stall Torque	1.2 Nm	0.15 Nm
Speed	6990 rpm	650 rpm

4.1.4.6. Transmission Selection for Joint 3

As in other circumstances already witnessed, the first step is to compare required criteria utilising the graphical approach. Doing so will allow for the selection of a specific component through comparison across a range of criteria.

Immediately an issue is encountered, though not to do with the framework. There is a very sparse range of worm gearboxes available at the torque range desired. In compiling the graphs, information was sampled from RS components; however, the supplier has since changed stock meaning that very limited worm drives are now carried. As such, many of the solutions provided in figure 62 are sourced from a variety of suppliers. There is also a larger than “normal” disparity in the X-direction, as highlighted in figure 62’s exploded view.

As mentioned, this is not due to the framework itself, but is due to changes in supply linked to time. These same issues would be encountered using existing methods of component selection, so is not a “negative” point of *this* work, merely an inconvenience faced in this procedure.

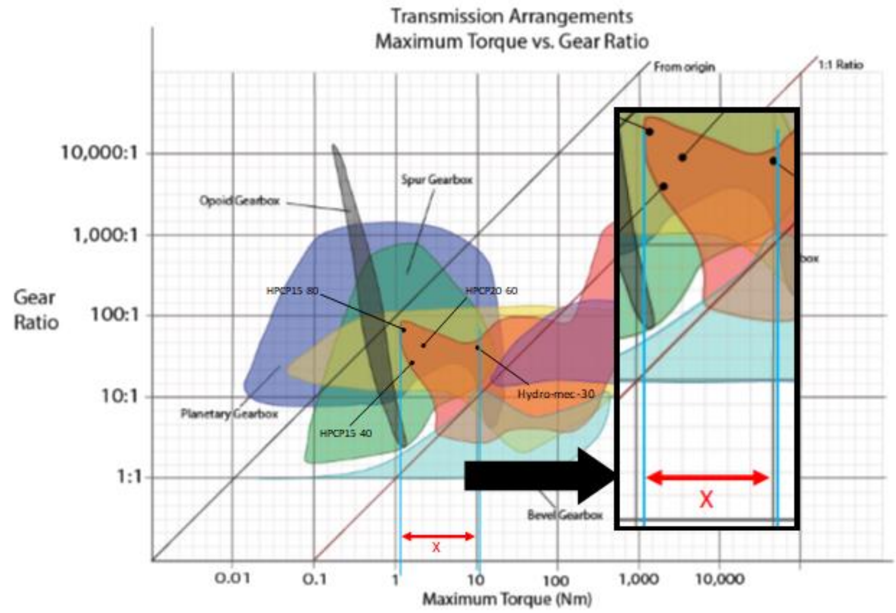

Figure 62: Initial comparison of available options for worm drives. Comparing to gear ratios. Note exploded image, where value X draws attention to large gap across torques considered due to issues sourcing appropriate worm drives at lower torques.

After deliberation over graphical information, the HPC P20-60 gearbox is selected. This selection has been affected by the sparsity of worm gearboxes encountered at the torque range of interest, as detailed. Owing to this restricted sample, an alternate gearbox was also selected to better assess the utility of the graphical approach when relying on a more complete sample dataset. A very positive outcome was able to be attained, as per table 16.

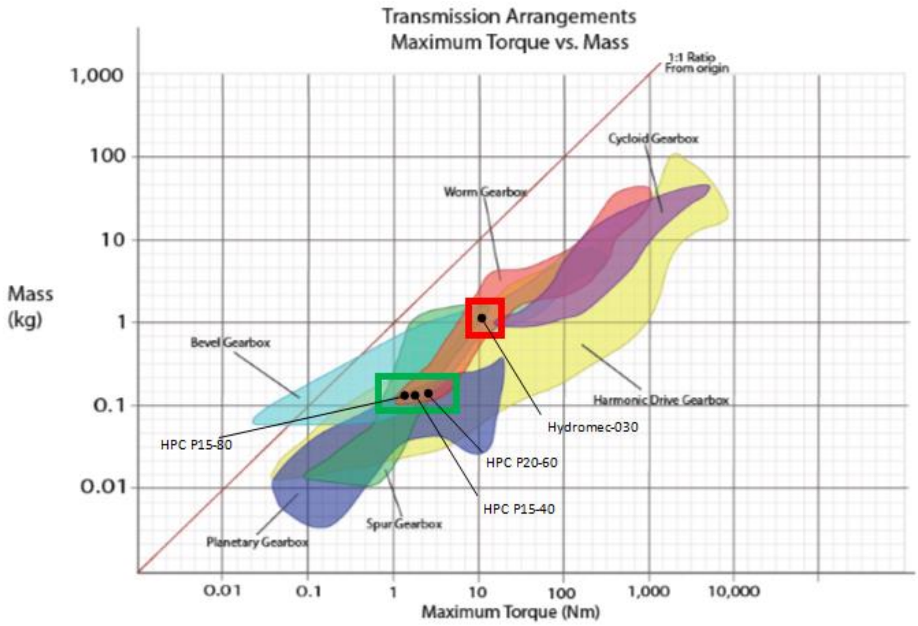

Figure 63: When comparing against mass, the lightest options are taken forward and heavier options omitted from further consideration.

Table 16: Comparison of an alternative component selected and the initial component selected.

Criteria	HPCP20-60	Maxon 110339
Maximum torque	4.1 Nm	**1.4 Nm**
Speed	6000 rpm	6000 rpm
Cost	£123.50	£123.91
Mass	0.18 kg	**0.068 kg**
Gear ratio	60:1	**84:1**

Further condensed detail on this selection and remaining selections for case study 1 are provided in appendix C.4.1. Full detailed case study 1 overview can be found on Strathclyde University's PURE data repository.

4.1.5. Systems Testing

The system's ability to function has been tested via simulation and physical tests to ensure it performs as required. By simulating and then physically testing, selections can be verified for correctness I terms of enabling the system to perform. This facilitates evaluation and validation of how well the components selected using the framework met their brief, and therefore assessment of the framework's effectiveness in aiding this process.

Comparison have already been made based on cost, mass, energy efficiency, etc. However, it is also necessary to ensure that the system designed following this approach does perform as needed. Speed and torque outputs by the systems are therefore assessed to ensure that the system requirements have been met. Consideration of all parameters of the system will facilitate comparison between the original system and the redesigned system, facilitating discussion as to which system best meets the requirements of the design specification.

4.1.5.1. Simulation of Results

The performance of the arm was simulated utilising Virtual Robotics Experimentation Platform (V-REP), and modelled with Solidworks parametric modelling software. Figure 64 provides a summary of the simulations undertaken.

With reference to figure 64, joint simulations of the functioning systems are provided with the number of simulation corresponding to the joint to which it relates. The torque variance with time is given for joints 3 and 2 as they move through 180° arcs, whilst the same information is represented for joint 1 but covering a 360° arc around the Z-axis.

Achieving results was made more complex by V-REP's dynamics enginer struggling with the bespoke arm's form; however, eventually simulations were able to be achieved which demonstrate the arm functioning as required, as per figure 64.

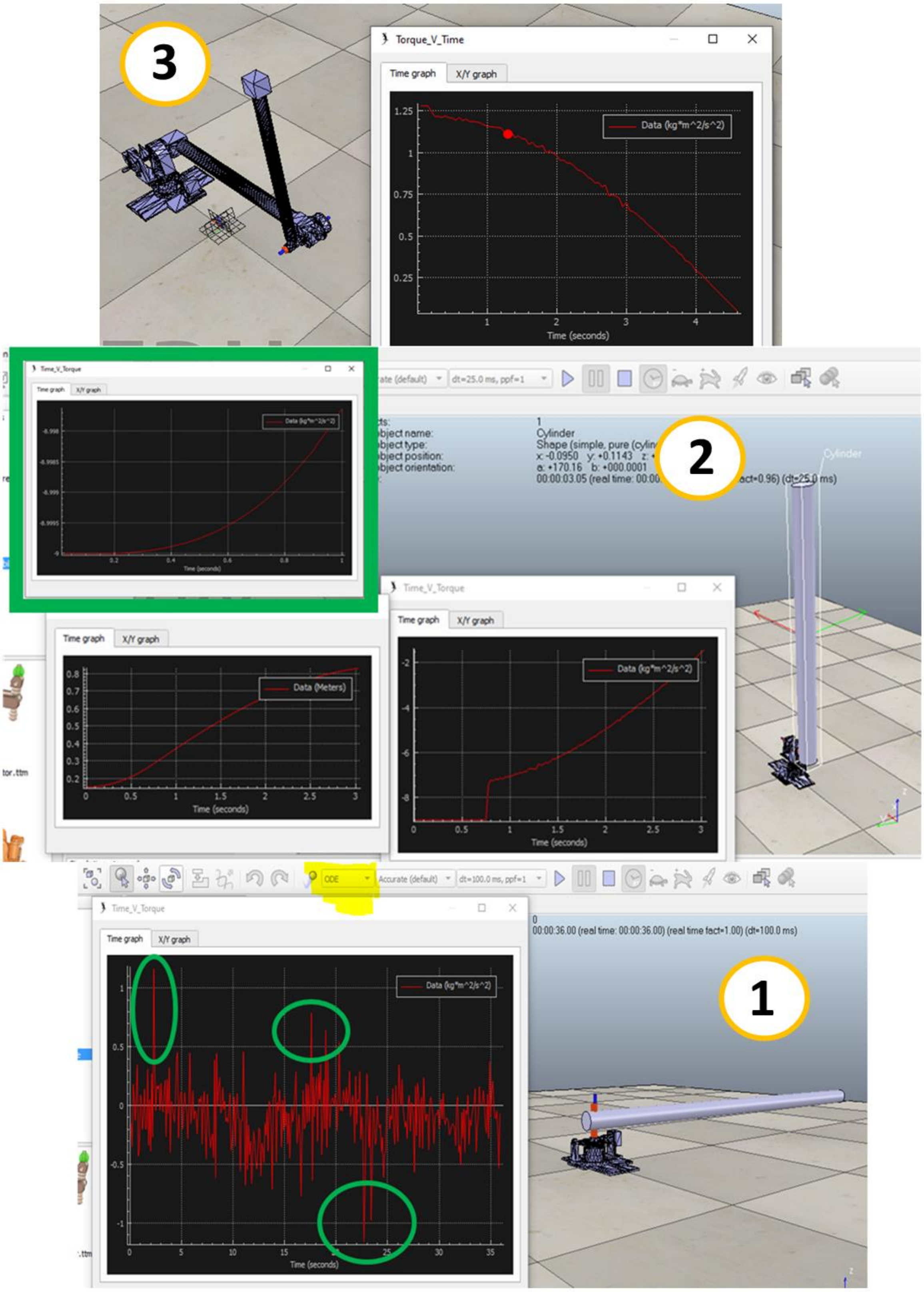

Figure 64: Overview of simulated results for the 3 joints developed using the framework proposed. Numbers denote joint number being tested.

4.1.5.2. Physical Testing of the System

Physical testing was conducted by adapting the arm as has been documented throughout earlier sections with minimal changes to mechanical design as detailed previously; only components of the system have been changed, as far as possible, with replacement fixturing developed where necessary. This enables closer review of effects of changing components, therefore allowing closer consideration of the affect the framework's use has had.

Results of Testing

The testing process is documented in figure 65, where images demonstrating the physical performance of the system are provided.

Joint 3

Joint 3 functions as expected. It is able to move as required and can facilitate movement of the defined load of 0.063 kg. It was tested up to >0.1 kg without failure, facilitating the needs of the brief with built-in contingency, as intended. The brake installed was also tested beyond its required load without any problems. The system was able to be run in closed-loop control successfully with the same accuracy as the existing system, as determined by the sensory hardware previously selected.

Joint 2

Joint 2 was required to manoeuvre a load of around 1.75 kg spread at various distances from the point of rotation. In testing undertaken, the system was assessed manoeuvring these loads and additional loaded at the end of arm. Lack of access due to Covid-19 restricted plans to make final measurements of the limits of the load capacity and assess speed limits of the system. The system has demonstrated that it can function beyond what is needed.

Joint 1

In joint 1 an issue was been encountered with performance, where the joint is not able to be rotated to the extent required. This issue is considered to stem from the selected motor not exhibiting sufficient torque to support movement as needed, with a number of potential contributing factors for this, summarised as follows:

1. One main issue in this joint is due to presence of dried out grease in the gearing, as arrowed in figure 66. This is something that was not foreseen, so could not be considered in selection. This solidification has affected the worm drive performance, increasing friction and making it more difficult to drive;

2. Transmission inefficiency may have been overlooked by the researcher to the extent required, resulting in an under-specified motor selection.; and,
3. Poor mechanical design/manufacture in the first instance may have had an adverse effect on the ability of the motor to operate worm drive as needed. There is axial compliance of the shaft upon which the worm gear is mounted, resulting in several millimetres of movement as indicated by the green arrow in figure 66, image 1. This is further suspected to affect the performance of the motor.

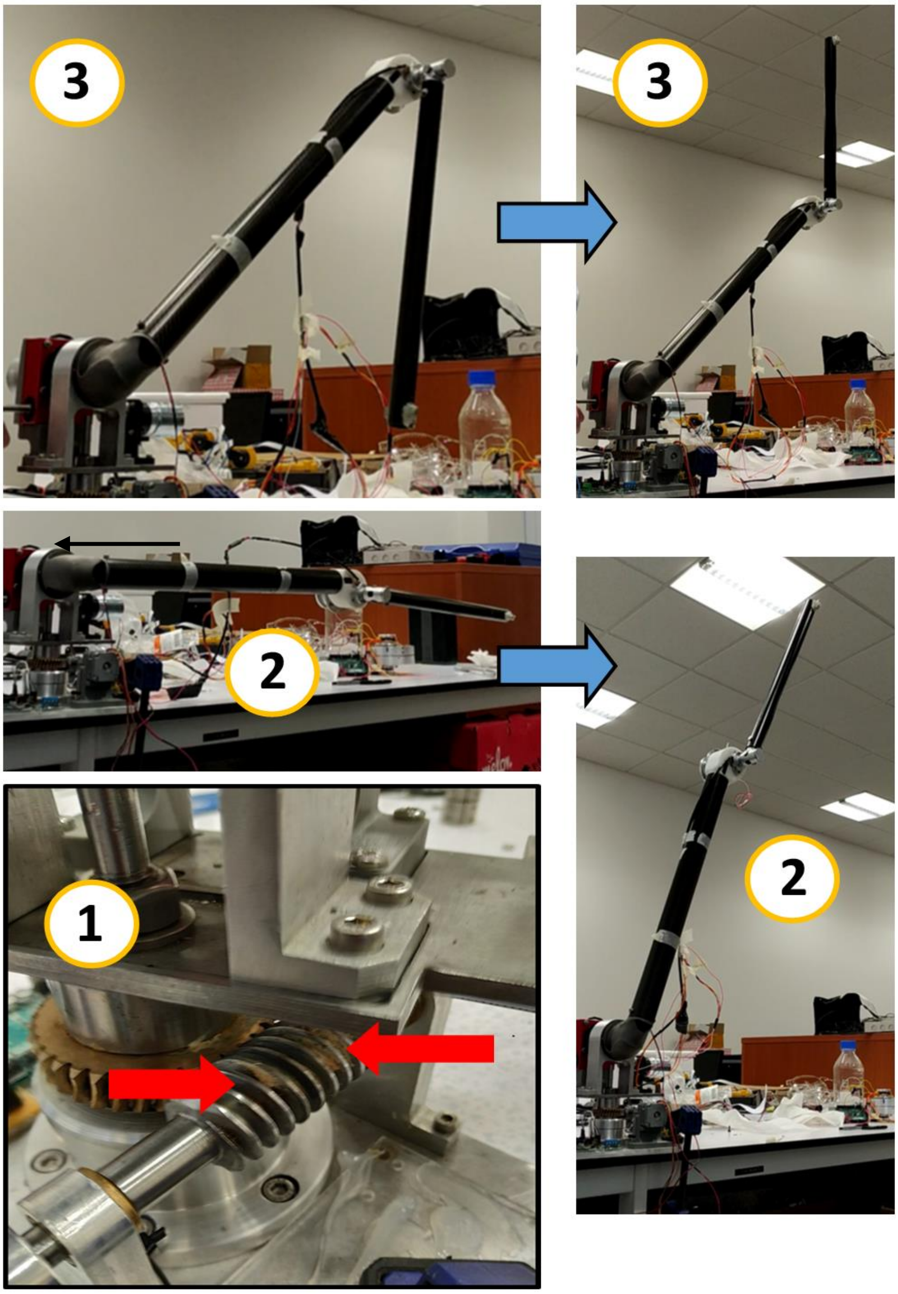

Figure 65: Overview of physical tests conducted. Numbers denote joint number being tested.

Cumulatively, points 1, 2, and 3 have added up to give rise to an issue where the motor is able to rotate through an arc from the red to the blue dashed lined in figure 66, image 2.

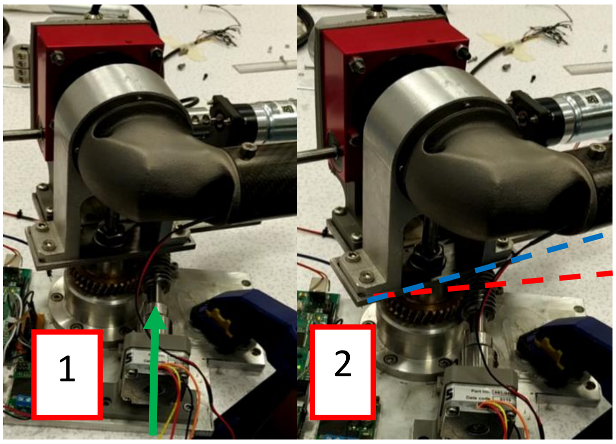

Figure 66: Limited movement achieved in joint 1. Issues encountered as described in main body. Image 1 shows start position, image 2 shows end position.

4.1.6. Conclusions on Case Study 1

A number of points and observations have been able to be made from completion of case study 1. These are discussed in the following sections.

4.1.6.1. Framework Assessment

The framework has shown promise and evidenced its ability to support generation of solutions to meet a design specification. The guidelines are shown to make sense, but have been highlighted as needing rectification in some areas. This has taken place prior to moving to CS2, facilitating evaluation of refined a refined.

The graphs show merit in quick and intuitive selection of components, but would benefit from some rough guidance on best practice for applying them. Obviously representing individual components has been a labour intensive activity in this thesis as it is applied manually, but the potential utility of this approach were it converted to a more fitting, software-based platform is plainly evident. The use of graphs has enormous potential as a means to reliability plot data of component performance and offer an alternative valid approach to the limited methods already utilised.

Testing of the components selected has shown not only that the framework works, but that it is at least as capable of selecting useful components as existing approaches utilised by experienced (5+ years industrial/academic experience) and well-qualified (Ph.D./master's degree level) engineers. The arguable exception to this has been in the development of joint 1. Requirements have failed to be met due to a combination of factors already outlined, which are not specific to the framework. Application of this framework has facilitated mass, cost, and power requirement reduction of the system. From simulated and physical testing, it is also known that the system operates as would be expected (with an exception outlined); see table 17. The framework has supported a selection exercise where mass savings of **0.584 kg** (19% saving), power savings of **204.6 Watts** (80.9%) and cost savings of **£493.17** (39.3%) have been attained.

Table 17: Overall system comparison with old components versus new components selected using framework.

Criteria	**Previous Total**	**New Total**
Mass	3.067 kg	2.483 kg
Power	252.8 W	48.2 W
Cost	£1,255.18	£762.01

A range of learning outcomes have been gained into the ways and means by which the framework is effective, as well as specific learning about the validity of utilising performance AHP/indices to ratify and support selection choices, etc. A more appropriate component suite for the Agribot arm has been produced, showing that the framework is valid enough to produce functional solutions, which is a key interest of this work.

4.1.6.2. Issues

Various small issues have been encountered, mainly surrounding teething problems of using the framework in its current state. Changing supplier catalogue has led to localised discrepancies too due to not yet having a process in place to automatically update a software platform to keep track of new components, fluctuations in price, etc. With respect to figure 62, a dynamic software package would have mitigate this issue entirely.

Issues of this ilk have shone light on other ways that the approach could be useful. Lack of standardised datasheets has been found to cause issue throughout compilation and selection during this thesis so far. It is also an often encountered issue in the researcher's profession, and is argued that one central platform which represents information would *greatly* mitigate this issue and would speed up selection and confidence in components selected. This supports the suggestion of the need for comprehensiveness intimated in other works (Cebon & Ashby, 1997).

4.1.6.3. Remedial Actions Needed

In light of knowledge gained from case study 1, a number of changes will be made to the selection guidelines.

Another key outcome had so far been that the use of the graphs has been assumed to be intuitive enough that they require no guidelines. It has been considered that this has been an oversight. The use of the graphs should not be heavily constrained, as they should be utilised as needed – some high-level suggestions of how to best apply them would, however, be useful. In Discussion, section 5.1.3., the final version of changed guidelines are presented and discussed.

4.1.6.4. Comparisons with Initial Process Taken

During interview on the process adopted, some key points were noted which are of significance to the work conducted in this thesis. Answers gathered on the approach taken to select components confirmed a notable absence of reference to frameworks or methodologies to aid this process. This was enquired about; however, the responses alluded to lack of knowledge of frameworks and processes available. Instead, it was mentioned that experience from engineering design more generally was relied upon. It was also noted from interview that RS Components was heavily relied upon, corroborating earlier assumptions made that engineers' biases towards components and selection processes (or platforms) can adversely affect solution quality.

> *"Most of the components were bought in a short amount of time. What torque was needed was calculated and then went on RS Components and bought the component."*

An argument of this thesis is that selection should be facilitated by examining the options available, rather than necessitating engineers to interrogate (potentially) many tens of manufacturers or suppliers' catalogues. Comments like the above also in-part confirm other authors' assessments around biases in selection processes.

The inclusion and use of AHP to define criteria precedence is a key novelty of the framework proposed. A question has been specifically introduced and asked to establish the extent to which criteria precedence was considered. The answer confirmed that the precedence of criteria was arrived at without specific consideration, and the criteria were defined through *ad hoc* definition. A point was also made surrounding a perceived error: the interviewee mentioned that the reduction ratio employed in the initial design was considered to go too far, reducing the speed of the joint by a greater extent than intended:

> *"This joint should perform a bit faster, I think. When we did it, it was not as performant as we wanted. I don't think this system would be able to do the task it was asked."*

The same interviewee later outlined how the guidelines proposed in the framework and the method of interrogation presented via a graphical method would have been helpful to the process, and in avoiding issues such as this.

> *"It's a good starting point for engineers. Sometimes we don't prepare the requirement specification document and we quickly move to the design stage. So, this would help to facilitate the requirements document [being completed more robustly]."*

In addition to answers provided on how the framework presented would have helped this specific task, the interviewee also provided inputs which supported the argument that the framework proposed could be helpful to students of engineering, as it allows communication of information (using the graphs and the qualitative databanks) but via the guidelines users are also guided through the process.

4.2. Case Study 2 – Novel Actuator Development

Case study 2 has applied the framework to the design of a novel actuator, and seeks to build on the work of case study 1, as is detailed in section 1.6.2. In the interests of focusing purely on the application of the framework and its associated methods, details around the use case are provided in greater detail in appendix C.5., whilst the following sections detail key points of application of the framework.

Additional key points considered in this study are exploring the use of 3D graphs and their efficacy, whilst understanding is also sought to be developed about *where* the framework is best applied in the context of an overall engineering design methodology; the example chosen for this is Engineering Design by Pahl and Beitz, as it is a very reputable and well-relied upon methodology. This allows a large cross-section of engineers to understand where the framework is best applied in the context of a well-known design methodology. The steps advocated by Pahl and Beitz are provided in appendix C.5., for reader reference, as required.

4.2.1. Conceptual Level Design

The exact overlap of the framework with the engineering design methodology proposed by Pahl and Beitz is detailed at the end of this chapter; however, the initial steps outlined in Pahl and Beitz's methodology have limited applicability as far as interaction with the proposed framework. Since the methods employed by the framework list potential solutions, they have been found to be a useful resource as far as searching for working principles, as outlined by step 3 of Pahl and Beitz's methodology. With a more comprehensive conveyance of information through the framework, the effectiveness of increasing engineers' cognizance of potential solutions would be expected to increase.

The framework has shown promise in raising awareness of potential solutions, but has otherwise not been found to interact closely with other aspects of the earlier stages of Pahl and Beitz's methodology.

4.2.1.1. Application of Framework for Selection

Concept level selection is carried out in a similar manner as discussed previously in case study 1. Guidelines have proven effective in prescribing the operations required to define some of the best prospective components available. The components considered to be most promising for use in this instance are highlighted in tables 18 and 19, below.

Table 18: Actuator 2 solution variants.

Component	**Components considered**
Motor	DC Servo, Stepper, or BDC
Transmission	Planetary or Harmonic Drive
Bearings	Ball or Roller
Brake	*Not required*

Table 19: Actuator 1 solution variants.

Component	**Components considered**
Motor	Stepper or DC Servo
Transmission	Not to be used to save space
Bearings	Ball or Roller
Brake	*Not required*

4.2.2. Embodiment Application

Earlier points covered in the framework have been found to be useful in that they corroborate the guidance that the framework seeks to convey. Pahl and Beitz outline the need to define requirements, ascertain the importance of various criteria, etc. The first points of the embodiment-level guidelines overlap with many of the themes outlined as important by Pahl and Beitz. This is significant as it assists in corroborating the framework's consideration of the correct information in its process flow. Some key points raised by Pahl and Beitz have been found to have been overlooked by the guidance offered by the framework, which is something remedied at this case study's end, facilitating further testing in case study 3. An example of this is consideration of environmental factors and spatial constraints which affect component choice.

Early steps in this process allowed definition of the key criteria through use of AHP. Key requirements of the system are provided in table 20, whilst more specific definition of requirements for individual actuators is refined and provided in tables 21 and 22, also below. These steps are again in line with those defined through the framework, and have supported a clear and robust approach to definition of components.

Table 20: Key requirements of embodiment level solution for actuator 2.

Criteria	**Requirements**
Arm shape	Single rigid link of basic geometry with
Length of arm	Single link of 0.5 m.
Mass of arm	0.15 kg
Materials used	Not applicable; arm weight defined as a 0.5
Load at end of arm	0.1 kg

Table 21: Actuator 2 requirements.

Criteria	**Requirements**
Required torque	0.863 Nm
Required power	10 W
Required speed	20°/second = 0.35 rad/s^2
Inertia of arm and load	0.0056 kg m^2

Table 22: Actuator 1 requirements.

Criteria	**Requirements**
Required torque	0.86 Nm
Required power	10 W
Required speed	20°/second
Inertia	0.00115 kg m^2

4.2.2.1. Section of Actuator 2 Components

As per the requirements outlined in table 21, it is known that a minimum torque of 0.863 Nm is required to facilitate actuator 2 manoeuvring the load. Inclusive of an additional 50% factor of safety, the required output of the motor and transmission system must be a minimum of 1.3 Nm at a speed of 3.33 rpm.

A novel element of case study 2 has been the use of 3D graphs as a means to interrogate information. This is as opposed to the 2D graphs already discussed in the previous chapter, and as applied in case study 1. Key torque and speed requirements were first plotted on the graphs, to facilitate assessment of this information, as per figure 67.

Interrogation of the graphical representation of component performance has quickly shown that limited options are available for the solution of interest, assuming a direct drive solution were to be attempted. As per figure 67, different 3D graphs are utilised to assess volume, which in turn enabled definition of the likely torque range which would be of use accounting for gearing. This process aided definition of what may be the best gear ratio to employ in the system. Graphs were again utilised to assess transmission options to establish the valid solutions available through graphical conveyance of key quantitative information, as per figure 69.

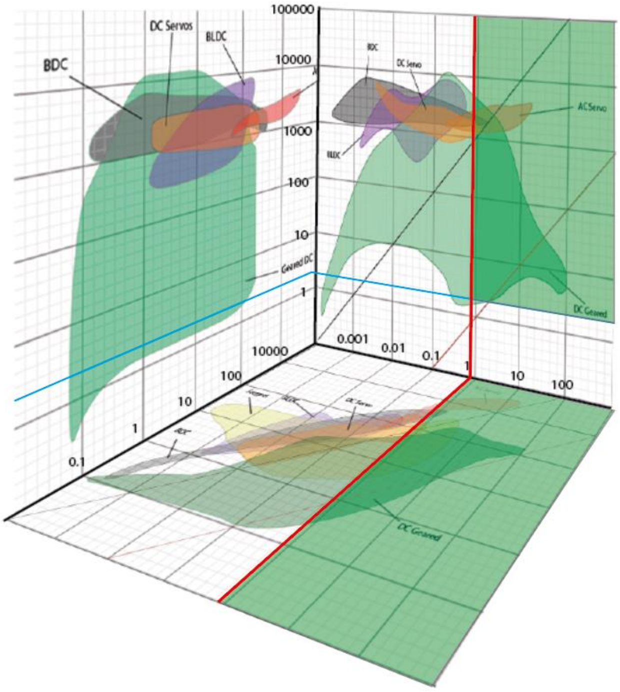

Figure 67: 3D graph highlighting direct drive motors which would be suitable in this application.

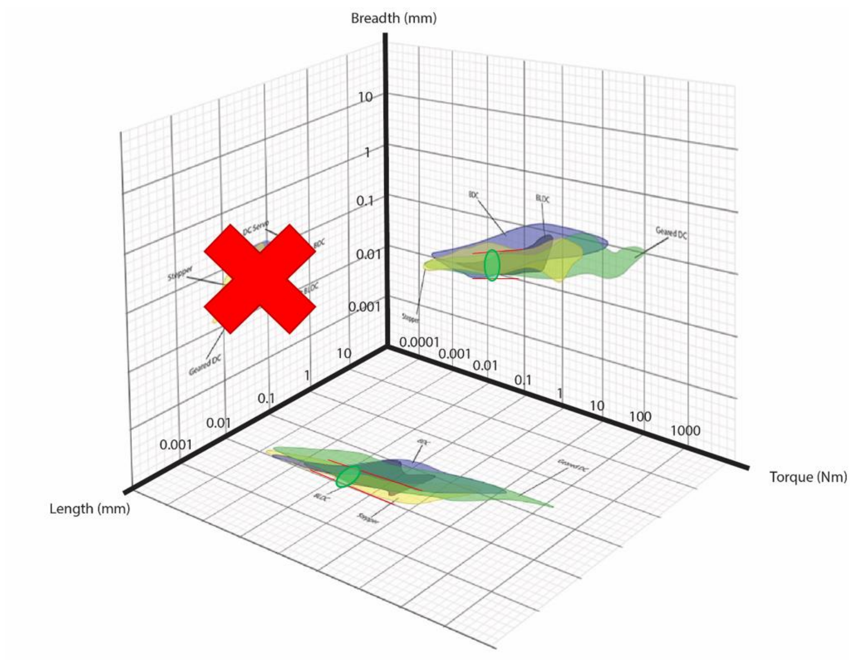

Figure 68: Red lines draw attention to the smallest lengths and breadths at the required torque range, with respect to prospective gear ratio.

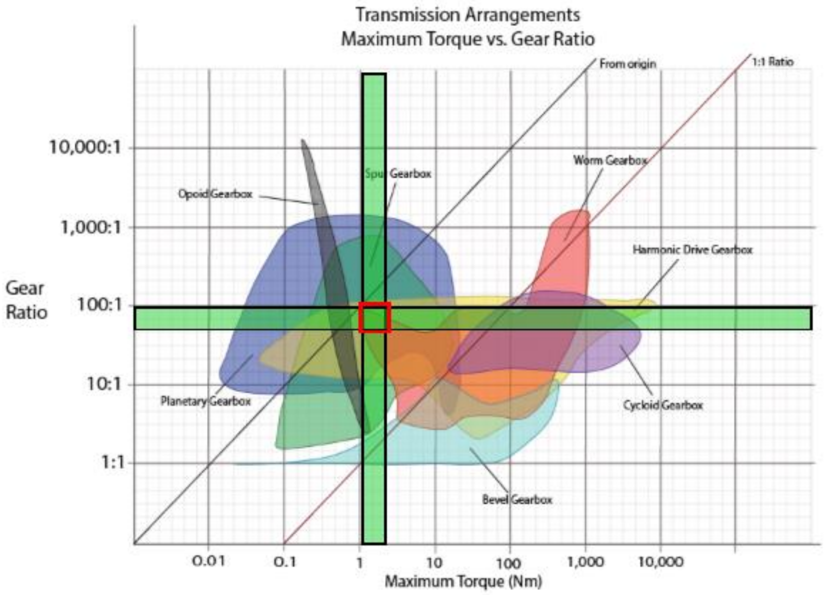

Figure 69: Best fit solutions for transmission of motor torque requiring approx. 90:1 amplification.

Interrogation of 3D graphs enabled understanding of the likely gear ratios required. Graphs conveying information on transmission's criteria draw attention to the region most likely to present a solution to meet torque **and** gear ratio requirements of this component. This process allowed definition of a Harmonic Drive gearbox, a planetary gearbox, or a spur gearbox as those best for further consideration. As before, the approach has facilitated rapid and systematic refinement of components considered, enabling an understanding of the rough geometry needed to fulfil performance requirements.

Motor Selection

Following refined shortlisting of components using the graphical method, generalised qualitative information about component types is interrogated. For motors and transmissions still under consideration, qualitative information provided feedback on concerns which the engineer should be mindful of, but did not raise any concerns which merit omission of a candidate component; concerns were mainly surrounding backlash in transmission systems and encoding position of various motor types. Consideration of both sets of information allowed the engineer to arrive at the conclusion to employ a DC servo motor with a Harmonic Drive gearbox.

Accounting for a transmission ratio of 60:1, a DC Servo motor producing at least 0.013 Nm and 330 rpm is required to meet the system needs. 3D graphs have been used to select a specific DC motor. Speed and torque performance are **required** from motors, as dictated by their high priority from AHP. AHP also cites the need to consider length, breadth, and height to reduce component volume. Figure

70 provides one such instance where initial comparison has taken place. Table 23 provides a legend for the colour coding of component instances as they appear on the graphs.

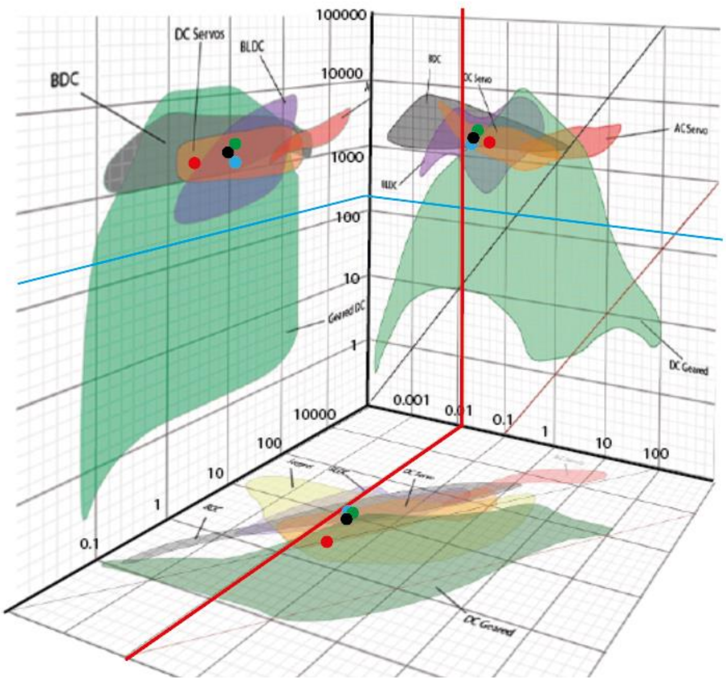

Figure 70: Torque versus Speed versus Power.

Table 23: Colour coding of candidate components.

Manufacturer	Model	Colour
McLennan Servo Supplies	9904 120 18105	RED
Pittman Ametek TIP	9234S006-R1	GREEN
RS Pro	263-5995	BLUE
Maxon	142750	**BLACK**

An interesting issue was identified in this study, where the information provided by RS Components on the McLennan Servo differs from the OEM's actual data. This issue was able to be noted through looking at the component plot on the graphs and noticing that the component was markedly different to other candidate solutions. This allowed the utility of the graphs to be demonstrated in a means not expected, but in a way which evidences the strength of interrogating information through this visual manner; patterns can also be noted and positive and negative aspects which appear are able to be conveyed noticed in this way. The visual interpretation allows understanding that the motor's information did not make sense. This is not the use for which it is intended, but demonstrates the range of ways representing information in this way can help quick assessment, and also draw attention to issues which may otherwise have been left unnoticed.

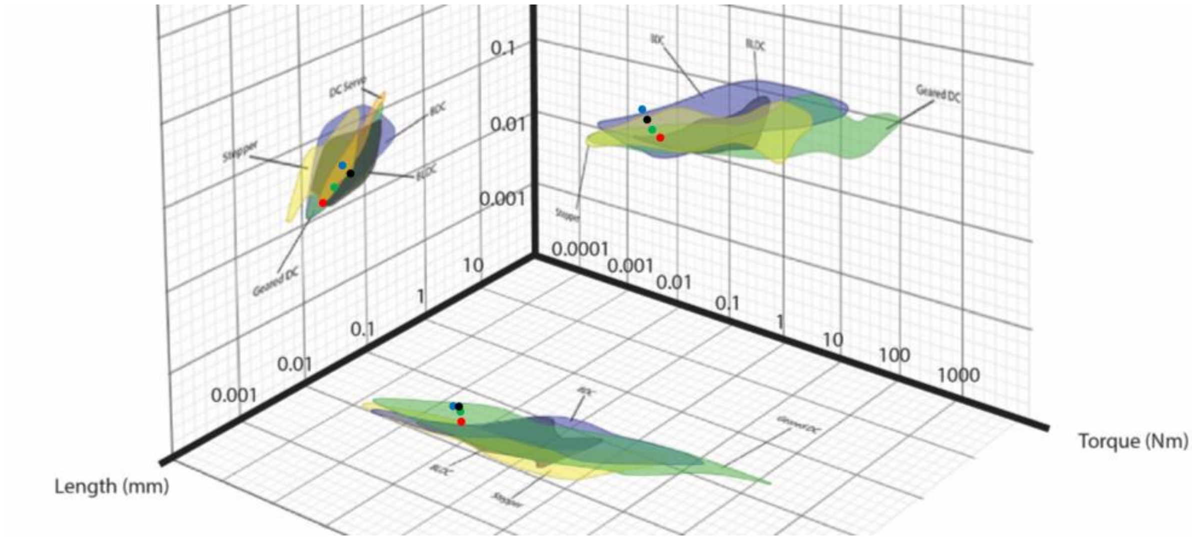

Figure 71: Torque Vs Breadth Vs Length.

Figure 71 compares across geometric information of considered components. It shows that the Maxon 142750 is an acceptable size motor, which better meets the power requirements than the Pittman Amatek model (green). The McLennan motor (red) would have been ideal, but for the issue outlined regarding incorrect information from RS Components. Figures 72 and 73 allow assessment on other, desirable, criteria, where the Maxon 142750 also performs favourably, allowing robust decision-making to be facilitated intuitively.

Figure 72 assesses components' mass and cost information, allowing intuitive selection of cost and mass-effective COTS solutions. The Maxon 142750 represents the lightest and most expensive solution of the 3 under consideration in this example. From AHP it has been established that cost is a low priority, but it is desired that the weight is reduced. As such, the Maxon motor represents a good solution in this instance. 3D graphs have been effective in allowing rapid comparison between criteria, in some ways more than 2D graphs provide, a process which has yielded the **Maxon 142750** as a suitable solution.

Of the 3D graphs, the information presented on the Y-Z plane has proven to be an extremely useful means of rapidly assessing the best "function costed" solution for two other criteria. The use of 3D graphs has seemed positive in this instance, but in more complicated instances it is considered that 3D graphs may become difficult to read and interpret. Without some additional step to mitigate this issue, the use of 3D graphs may add more complexity than the upside they yield. That being so, it may be worthwhile continuing to develop 3D graphs in future work to further explore their merits.

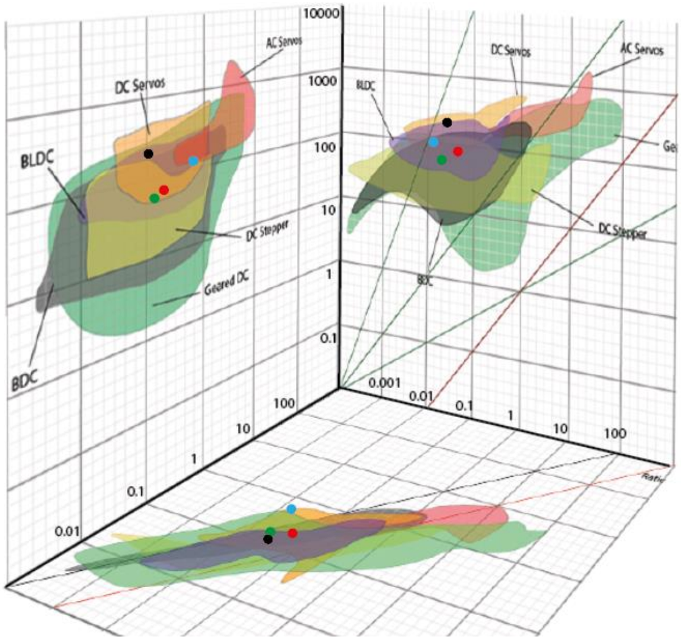

Figure 72: Torque Vs Mass Vs Cost

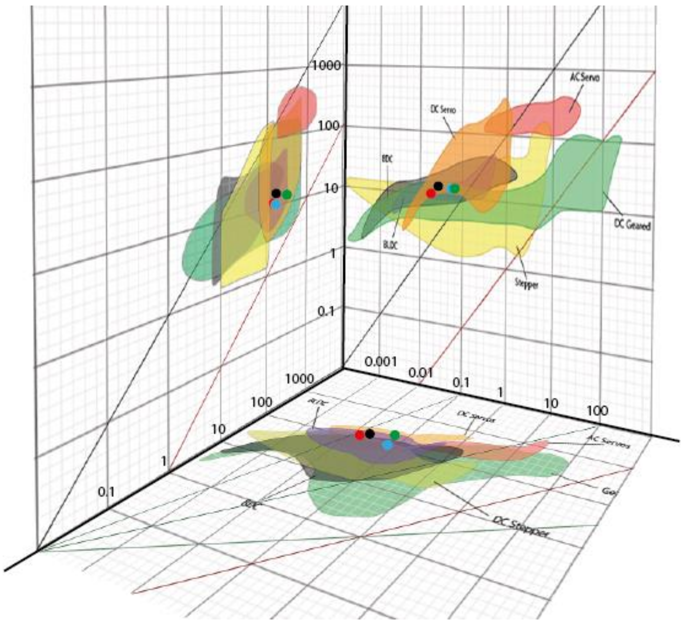

Figure 73: Torque Vs Rated Voltage Vs Cost

Transmission Selection

Figure 74 provides an overview of the main components considered in selection of a transmission for actuator 2. It should be noted that all solutions considered are Harmonic Drive Gearboxes. The only **requirements** of the transmission are that it operate at the required speed and torque ranges, ideally in the smallest space possible. Due to the quality of the component type being considered, there is no issue with speed or torque for the components under consideration. The selected component is detailed as follows.

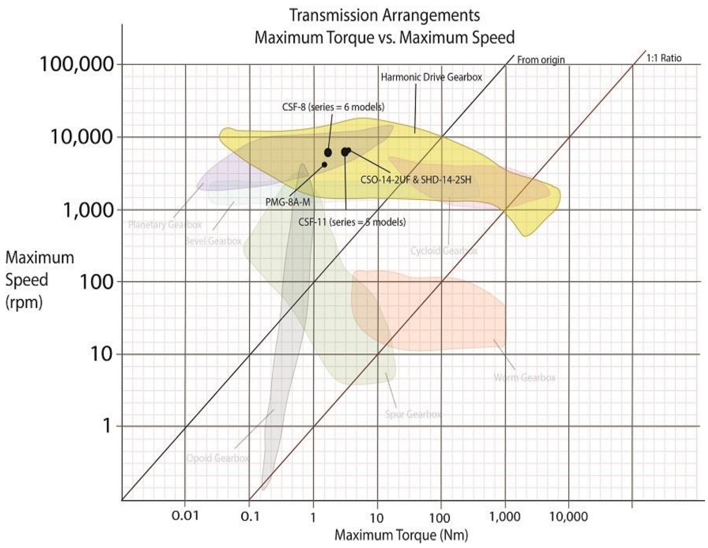

Figure 74: Torque Vs Speed

The **Harmonic Drive PMG-8A-M** with a 72:1 ratio has performed well throughout consideration. An informed choice about the selection of this gearbox has again been possible reliant on the conveyance of information from the graphs, supported by the guidance of the framework holistically.

4.2.2.2. Selection of Actuator 1 Components

Again, AHP has been leveraged to define the precedence of key criteria, whilst guidelines have also supported a process which facilitates the definition of key parameters relevant to the actuator being developed. The key requirements are documented below, as per table 24.

Table 24: Key criteria of actuator 1.

Criteria	**Requirements**
Required torque	0.315 Nm
Required power	9 W
Required speed	20°/ second = 0.35 rad/sec
Total inertia of disk and mounted components	0.002 kg m^2

Selection of a Specific Motor

The same process as before can be reapplied in order to select a motor for actuator 1 in this case study. Figure 75 provides an overview of the components considered, expanding to demonstrate their similarity in torque v breadth consideration. Remaining application can be viewed in section D.6. of appendices. A Sanyo Denki 103H5210-5240 stepper motor has been eventually selected.

Since a key desire of this system is reduction of mass and volume, no transmission is used and the motor is instead run in direct drive.

4.2.2.3. Select suitable preliminary layouts

Components have been selected which are expected to deliver a capable solution. Since the exact layout of the actuator package is not known, there may be a need to change components to fit within the system. Where parameters change in the process, the selection process can be repeated as necessary to find the right component set-up. Specifics of reconfiguring to refine solutions are difficult to forecast, and across numerous methodologies (Stuart Pugh, 1990) (Bietz, 2007) (Ulrich & Eppinger, 1994) specific guidance is quite diffuse.

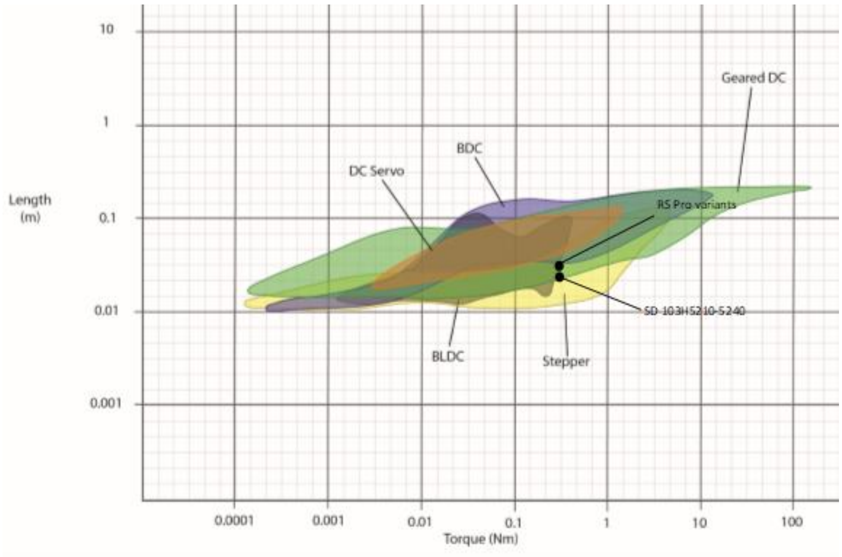

Figure 75: Comparison of systems based on torque against breadth.

Similarly, the guidelines developed so far are also quite diffuse in dealing with this refinement and iteration process. The framework has milestones to “check” that solutions conform to the requirements of the system, but guidance on iteration is not provided in the framework. As discussed already, the guidelines are noticed to be too “insular” in terms of considering the physical environment, but consideration of the need to iterate is something which should be accounted for.

4.2.2.4. Develop preliminary layouts and form designs for the remaining function carriers

It is argued that the remaining components which have, as yet, not been dealt with are the “remaining function carriers” (page 230, Pahl and Beitz, 2007) referred to. These are considered to entail couplings, mating flanges, etc.

The housing would be manufactured and machined from aluminium, couplings may be necessary, and various flanges, etc. may also be required. It is considered that other components necessary have already been addressed through selection of primary function carriers, with the assistance of the framework. The framework is not considered relevant to this stage of system development.

4.2.2.5. Search for solutions to auxiliary functions

Auxiliary Functions are described as "…those which contribute indirectly" (Bietz, 2007) to the overall function of a system. Auxiliary functions are considered to be the user of components such as bolts, nuts, springs, bore reducers, etc. It is considered that this section facilitates bearing selection, as an auxiliary function.

Actuator 2 – Bearing Selection

The last remaining component to be selected in actuator 2 is the bearing. AHP for bearing selection is provided alongside the key tables utilised in selection.

Table 25: AHP outputs for Actuator 2 in Case Study 2.

Criteria	Percentage	Order of Precedence
Dynamic Load Rating	35.4%	1
Cost	4.3%	5
Mass	8.3%	4
Static Load Rating	27%	2
Outside Diameter	25%	3

AHP results determine that the requirements to deal with dynamic and static loads are met, whilst OD size is prescribed the most important of the desirable traits in this instance. It can be seen from figure 76, that the AXK 1024 provides the smallest option available from the components sampled. It is mass and SLR are also compliant to the requirements of the actuator.

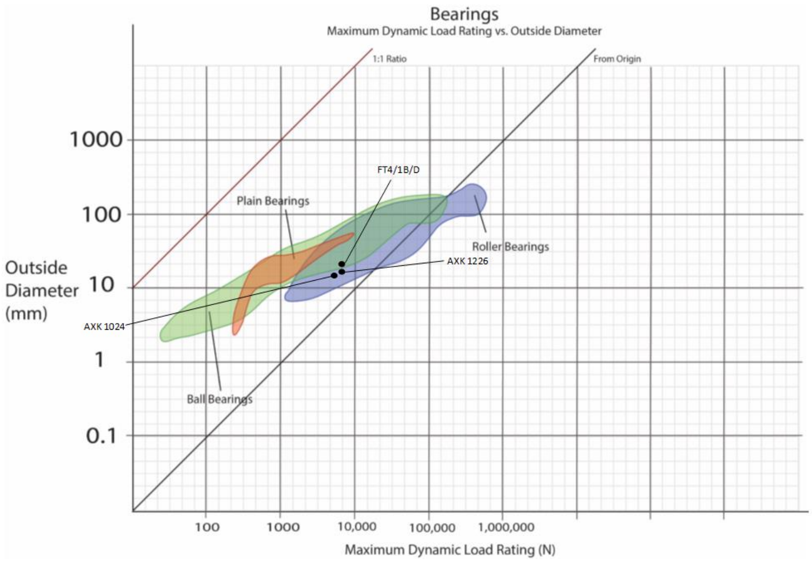

Figure 76: Overview of selection relative to load limit and OD of roller bearings.

4.2.2.6. Develop detailed layouts and form designs for the main function carriers ensuring compatibility with the auxiliary function carriers

Pahl and Beitz next encourage definition of detailed layouts and forms for the system's design. This process entails developing something close to the final form of the system. Components have already been selected, as demonstrated earlier; however, this step *may* necessitate some component changes. If necessary, the component selection framework can be used in the same way used already, only for reconfigured system requirements.

This step is not directly relevant to the use of the framework, but can have significant relevance to utility of the framework dependent on the circumstances.

4.2.2.7. Develop detailed layouts and form designs for the auxiliary function carriers and complete the overall layouts

This section is a continuation of the selection processes already employed. Steps 3 and 4 have determined *main function carriers*, meanwhile step 9 will concretise the forms which main and auxiliary function carriers take.

At the current stage of development, this is not considered relevant to the framework.

4.2.2.8. Evaluate against technical and economic criteria

The framework has been shown to assist in comparing required and desired economic, technical **and other** criteria. This is designed to make the approach as thorough as possible, using requirements which are methodically identified and prioritised using AHP.

Evaluation of components selected has taken place already during selection to the extent expected during such processes. The guidelines do not extend to facilitate simulation and testing for evaluation, as this is not a bespoke element required of the guidelines. In this case study, simulation has been used as a means to evaluate whether the components utilised will meet the requirements of the system.

In order to assess the performance of the system (and by extension the validity of components selected following the framework's guidance), dynamic simulation has been undertaken. A range of simulations have been undertaken, as summarised in figure 77, below. As in case study 1, the actuator simulation is numbered to correspond to the actuator being tested.

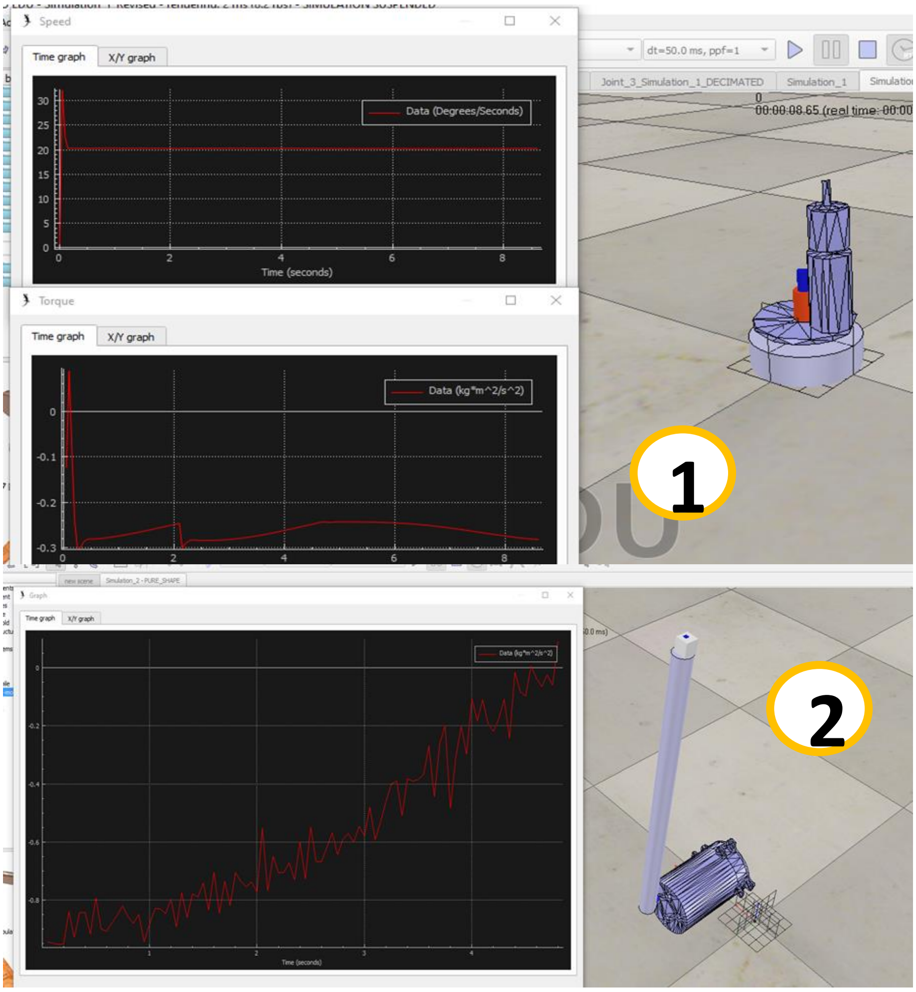

Figure 77: SImulation of Novel Actuator Performance. Numbers correspond to actuator numbers.

Figure 77 provides an overview of the performance of both actuators, evidencing that the appropriate torque is able to be delivered and the desired movement arcs have been attained at the speed desired. From the results of multi-body dynamics simulations, it has been shown that the torque and speed output **requirements** have been met, as documented in tables 26 and 27.

Table 26: Requirements of actuator 1, with highlighting. Green shows goals met, grey is N/A, and orange is not measurable in simulation platform.

Criteria	**Requirements**
Required torque	0.315 Nm
Required power	9 W
Required speed	20°/ second = 0.35 rad/sec
Total inertia of disk and mounted components	0.002 kg m^2

Table 27: Actuator 2 requirements. Colourized to show achievement: green for achieved; grey for N/A; orange for not able to be measured.

Criteria	**Requirements**
Required torque	0.863 Nm
Required power	10 W
Required speed	20°/second = 0.35 rad/s^2
Inertia of arm and load	0.0056 kg m^2

4.2.2.9. Remaining steps

With reference to the steps advocated by Pahl and Beitz, several steps remain. None of these steps of are great significance to this framework proposed.

4.2.3. Summary

Case study 2 has built on knowledge gained from applying the framework in case study 1, corroborating assessments from case study 1, and highlighting further issues allowing them to be remedied. It has also been possible to make new claims about the applications and effectiveness of elements of the framework, and new lessons have been learned about some of the idiosyncrasies of the framework. These are succinctly highlighted in the following statements;

- The framework has shown evidence of sensible and logical step-wise instruction, facilitating intuitive component selection.
- Some localised discrepancies in the guidelines have been found and are to be remedied post-case study 2. As noted in previous sections, final guidelines are presented and discussed in the following chapter.
- The graphical method of conveying component performance has proven to be a useful tool in facilitating rapid and intuitive component assessment.
- The tools used in the framework (graphs and the qualitative overview) have proven a useful reference tool in supporting the *generation* of solutions and in allowing refinement towards selection of individual solutions – an unexpected outcome;
- A wealth of understanding around how the framework operates in conjunction with system design methodologies has been gained. This promotes clearer understanding of when and where to use the framework to best effect. The specific overlap is presented in figures 78 and 79;

- The use of 3D graphs has proved to be valid, though has been noted to add complexity. It has also been shown to support selection of specific components, however there are concerns about its utility generally, especially when utilised not on a software platform; and,
- The framework has been shown to support novel actuator design, demonstrating the versatility of the approach. The approach has proven to be effective in assisting in different types of task both within case study 2 and in comparison with the tasks undertaken in case study 1.

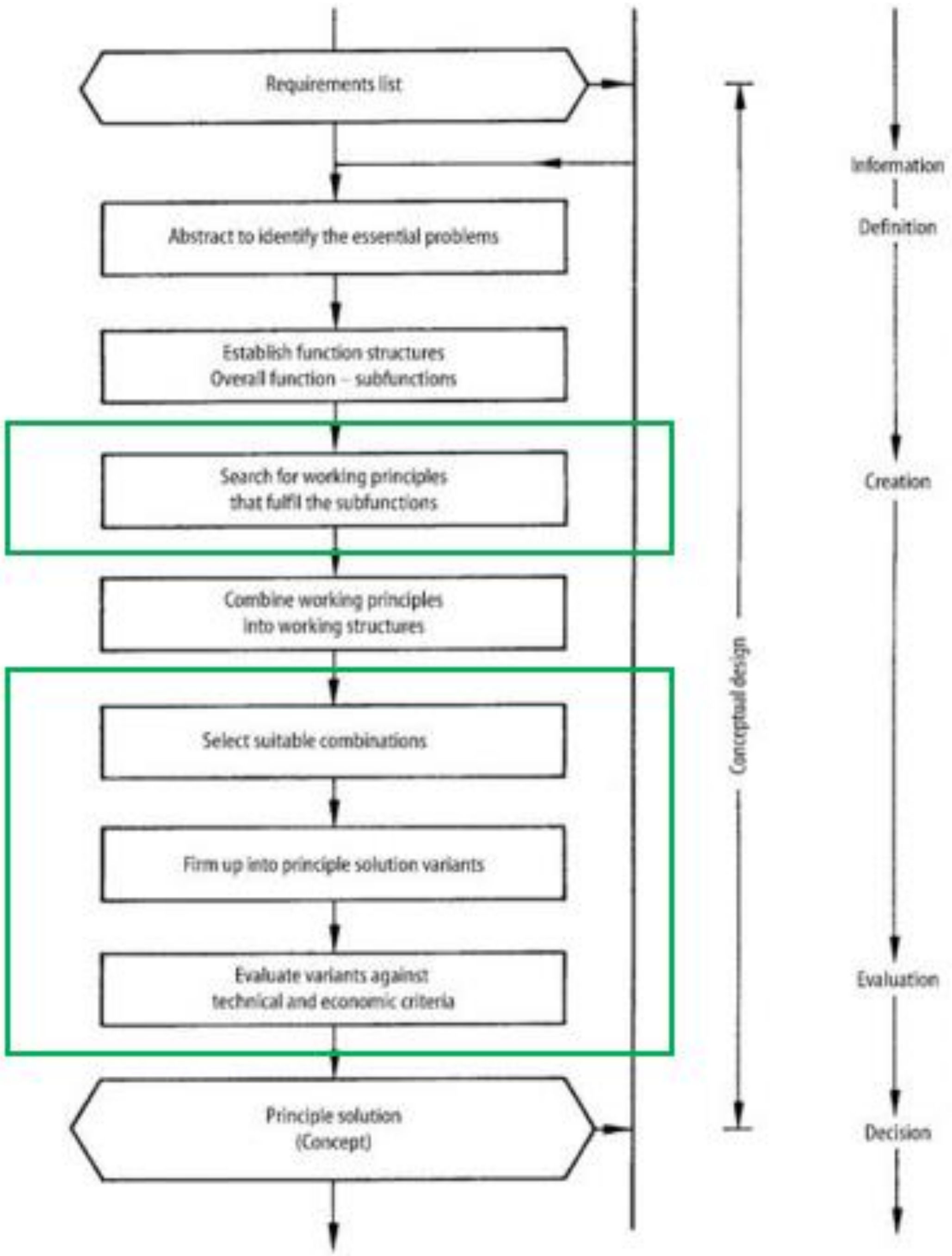

Figure 78: Key points where framework is applicable withint Pahl and Beitz's concept-level "steps".

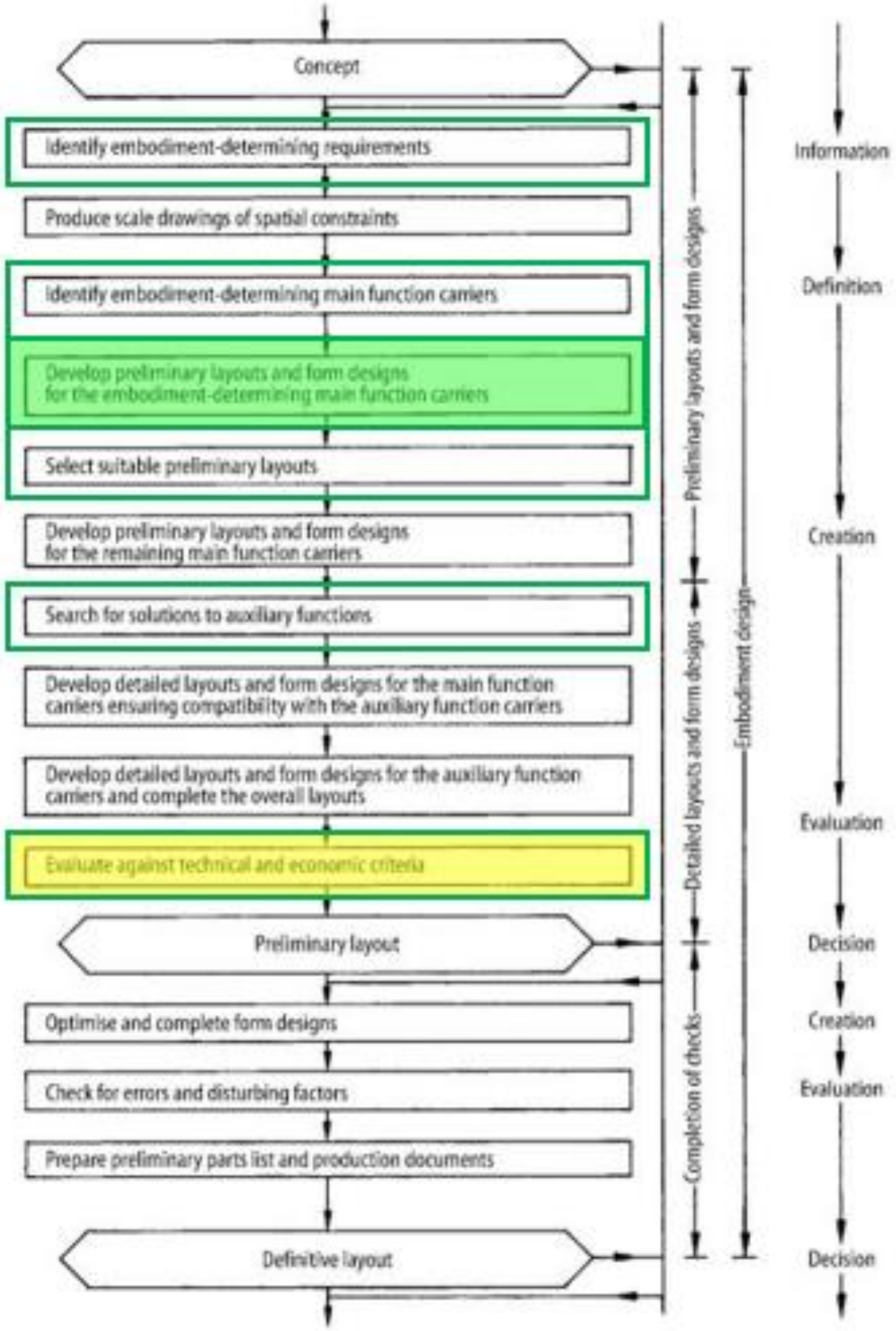

Figure 79: Overlap of framework applicability within Pahl and Beitz's embodiment "steps". Green fill denotes selection of motors and “primary” function carriers, and yellow denotes bearings, etc.; “auxiliary” function carriers.

4.3. Case Study 3 – Advanced Forming Research Centre Robotic Demonstrator End Effector Design

This report covers the development of a demonstrator for the Advanced Forming Research Centre. At this stage in development, it was sought to complete this task as cheaply as possible as a prototype system. Detailed background and breakdown of initial processes can be found in appendix C.9.1. Concept level application is provided in appendix C.9.2.1., in aid of expediency.

4.3.1. Embodiment Design of Demonstrator End Effector

As previously, AHP and more specific definition of the system requirements are generated, with the key requirements for actuator 2 are summarised in table 28, below.

Table 28: Actuator 2 system requirements.

Criteria	Value
Power	0.016 kW
Torque	0.044 Nm
Speed	3,500 RPM
Inertia	$\mathbf{120 \times 10^{-9}\ kg\ m^2}$

As documented already, cost is the priority of this selection process. Figure 80 begins by considering torque against cost to establish suitable systems with reference to this key criteria. Figures 81, 82, and 83 present graphs which have facilitated interrogation on varying information across varying component types, eventually facilitating definition of suitable candidate components for fulfilment of the task's requirements.

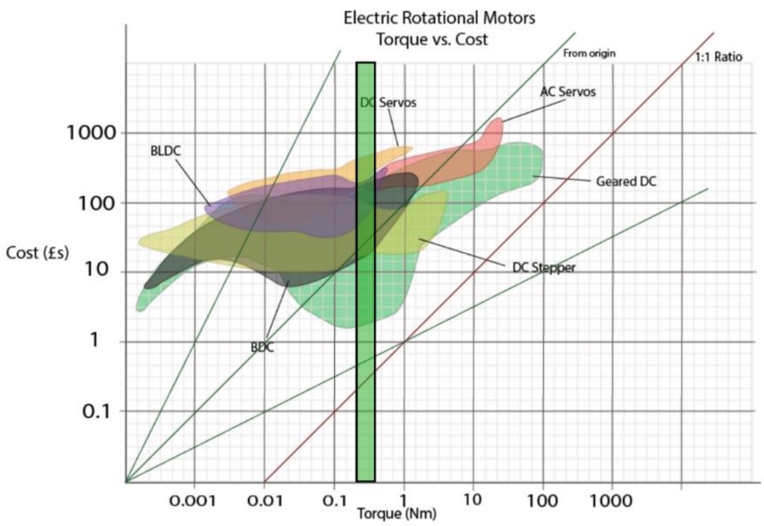

Figure 80: Torque plotted against Cost. Green region highlights viable options when gearing at a 10:1 ratio to increase speed.

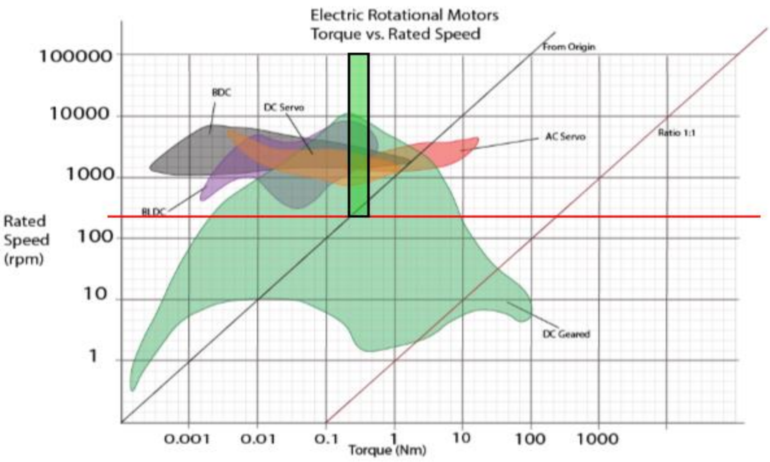

Figure 81: Torque plotted against Rated Speed. Green region highlights viable options when gearing at a 10:1 ratio to increase speed.

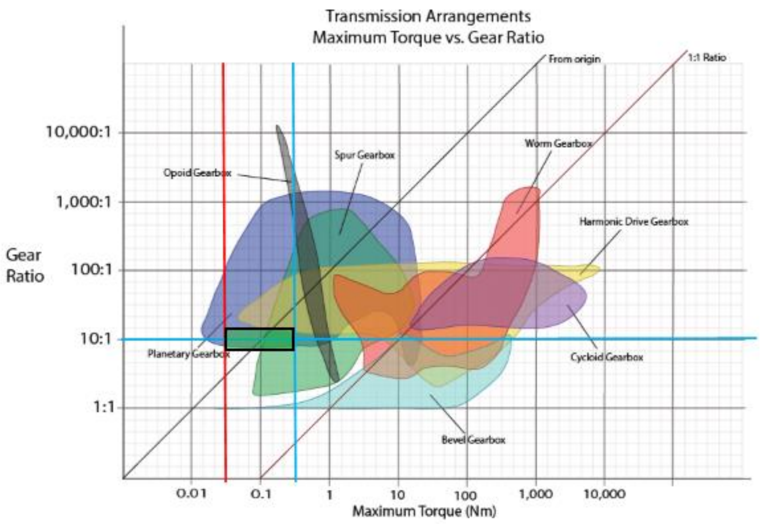

Figure 82: Maximum Torque plotted against Gear Ratio for transmission types. Most viable options are highlighted in the green region.

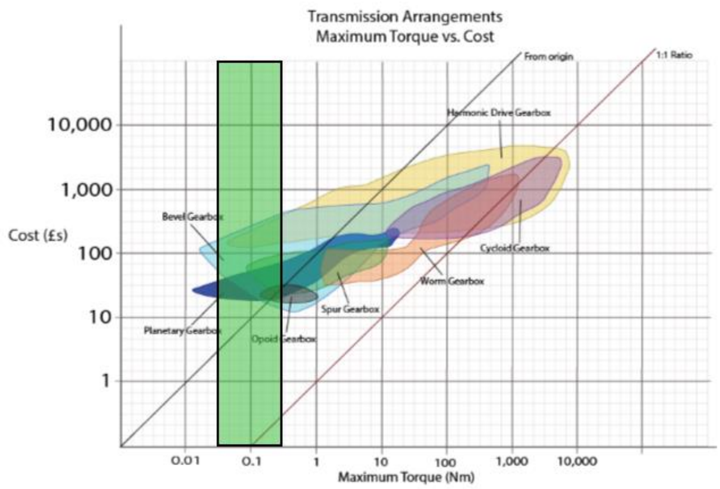

Figure 83: Maximum Torque plotted against Cost for transmission types. Most viable options are highlighted in the green region.

It has been shown how the information in the graphs can be used to draw direct information; however, the information also allows the user to make inferences and manipulate the information. Averages to develop approximate costing for the best or worse-case scenario can be developed across a particular range, for example. In this case, reasonable solutions are compared in table 29 to reach a decision. Localised averages have been generated quickly based on the boundaries of the graphs within a particular torque range of interest; by considering an average of a *specified range* of a Y component, rather than the *complete range*, this process can become more accurate in a multitude of ways. With a more comprehensive dataset represented, one can easily imagine how the power of the graphs could become even stronger.

The comparison enabled by the graphs in summarised in table 29, below. This comparison has enabled definition of a logical approach which is expected to reduce cost of developing the system to the requirements of the task.

Table 29: Breakdown of the costs of applying actuating function.

Approximate Costs	**Direct Drive (average cost)**	**With Transmission (average)**	**Direct Drive (cheapest available)**	**With Transmission (cheapest available)**
Motor	£50	£50	£10	£10
Transmission	N/A	£50	N/A	£30
TOTAL	£50	£100	£10	£40

4.3.1.1. Selection of a motor

In this chapter that there are a number of instances components start to become quite distributed in terms of the X-component of the graphs. This is suspected to be because this case study was conducted more than 1 year after the database was developed, meaning that the source of the database being used has significantly changed its product catalogue. In a developed version of this platform, a much larger range of components would be compiled in the first instance and would be kept up to date, completely mitigating this issue.

As per figure 84, an absence of motors operating within the narrow 0.04 – 0.06 Nm range existed from the sample database being used. In order to better facilitate discussion on the applicability, effectiveness, and capability of the graphical method used at this stage, the torque range was expanded out to cover 0.04 Nm to 0.4 Nm.

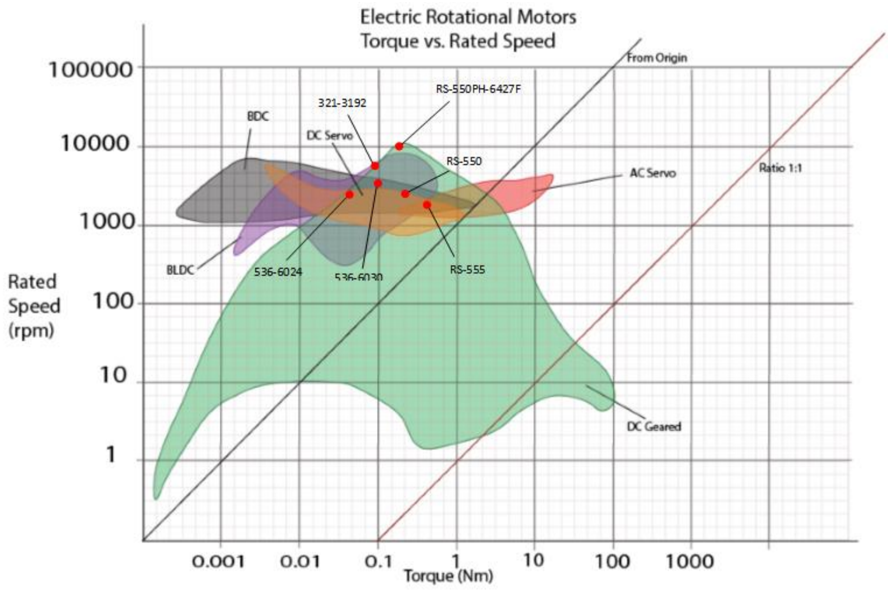

Figure 84: Shown above is the Torque as plotted against Rated Speed. The selection area, highlighted by the green box demonstrates that all

As per figure 84, there are a number of solutions available which meet torque and speed requirements. Figure 85 shows an upper limit of £40 has been instituted, allowing 2 components to be omitted; i.e. the criteria can be addressed in priority defined by the AHP process until criteria are exhausted, leaving only viable solutions remaining. Figure 86 compares based on mass, whilst other graphs have been utilised to compare remaining criteria.

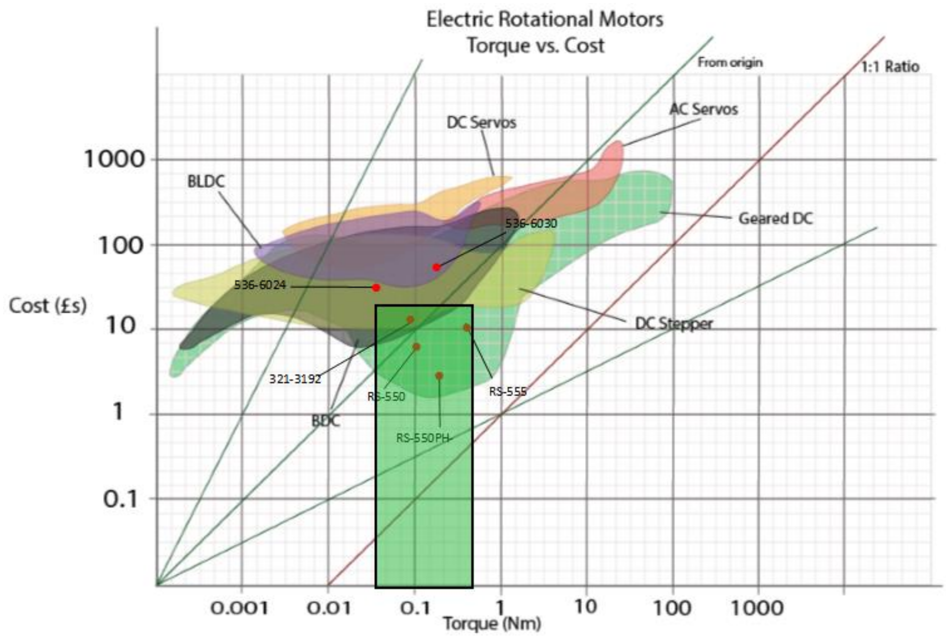

Figure 85: Considered components assessed against cost, with some removal of components facilitated, as indicated by highlighting, above.

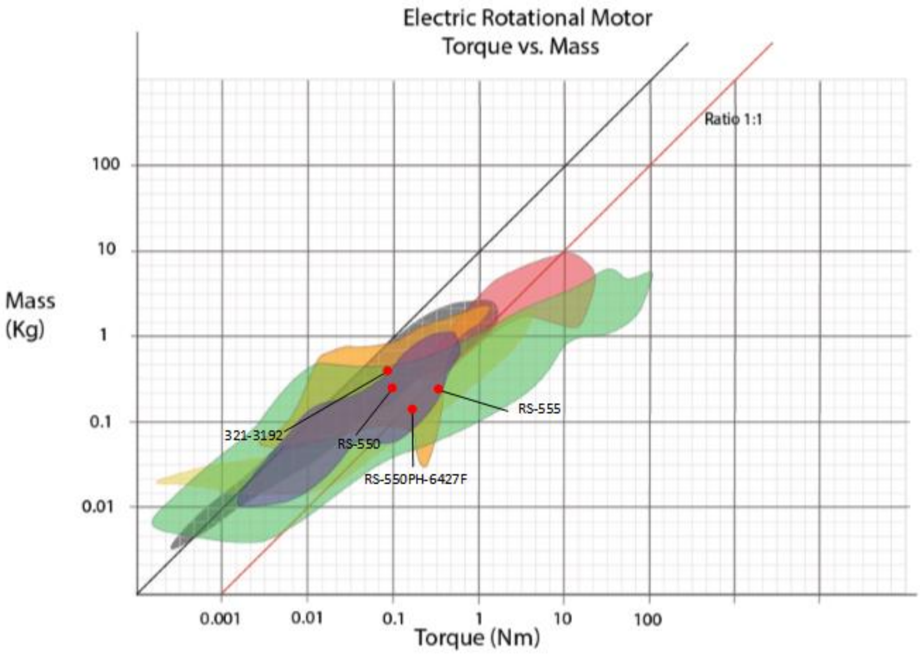

Figure 86: Torque versus mass.

From graphical plots the Mellor RS-550PH-6427F is the outright lightest and cheapest, and offers ample speed. In terms of function-costing, it can also be seen that the RS-550H-6427F is the best function-costed solution in terms of cost, and second best in terms of mass. Assessment of the performance indexes was also undertaken, with positive return. From this process, it is demonstrated that the RS-550H-6427F provides a better function-costed solution.

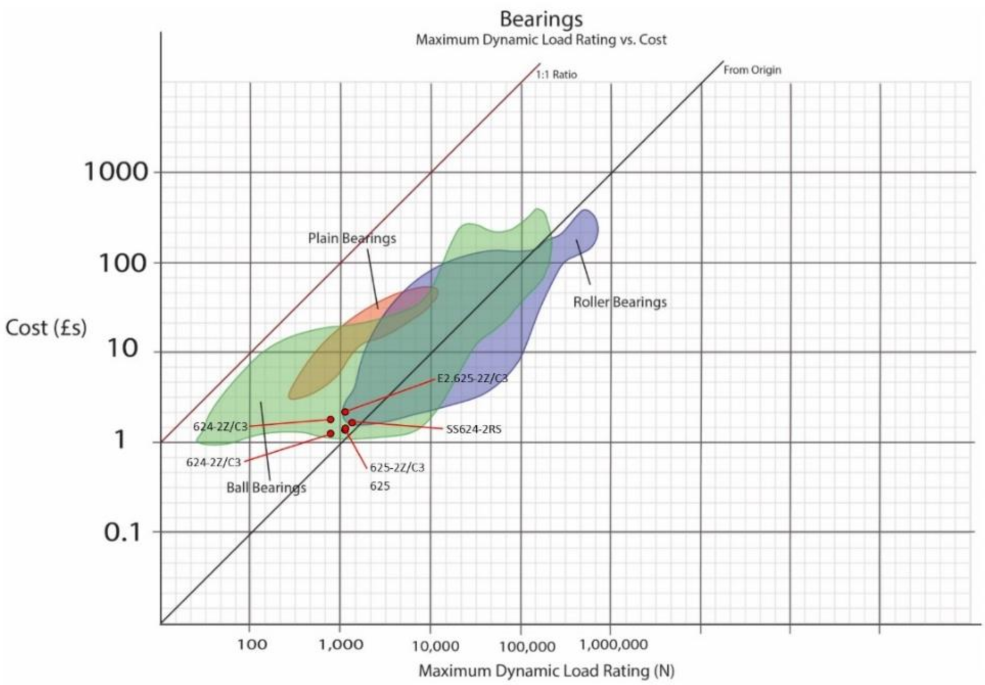

Figure 87: Bearing seletion graph utilised.

4.3.1.2. Selection of a bearing

The main criteria of assessment for bearing selection is again a functioning solution, attained at minimal financial cost. The use of graphs to assist this process is demonstrated in figure 87.

4.3.1.3. Selection of Components for Actuator 1

As before, criteria precedence for selection is established. Also as directed by the framework, the key requirements of the actuator are documented. These requirements are documented explicitly in table 30, below.

Table 30: Re-iterating actuator 1's required performance.

Criteria	Value
Power	0.103 W
Inertia	$\mathbf{5.56 \times 10^{-3}\ kg\ m^2}$
Torque	0.588 Nm
Speed	10°/s = 1.6 RPM
Acceleration	10°/s^2

Positional control of actuator 2 is required, therefore there is a need to ensure that a solution which facilitates control of the system is available. This will involve consideration of the methods to achieve this. Arrangements will also need to be put in place to facilitate an appropriate gearing solution. The graphs can be used to quickly approximate the costs of this process in the same manner explored in assessing for average costs in actuator 2's development. The expected best and average case costs are summarised in table 31.

Table 31: Overview of costs associated with the positional control of actuator 1.

	Open loop	Open loop actuator with external sensor	Servo
Best case	£10	£15	£80
Average case	£40	£60	£300

With reference to figure 88, a stepper motor in open loop is argued to make sense. Red highlighted region shows potential DC Servo solutions, ranging from cheap to moderately-priced. Blue highlighted region shows range of stepper motor solutions, again, ranged from cheap to moderate in price. A similar process has been taken in actuator 1 as for actuator 2 to arrive at this conclusion, detailed in table 32. Inferences made from interrogation of information presented by graphs also dictated that a system without a transmission system would be preferable due to modest torque requirements and the need to reduce cost. Figures 89 and 90 show how the graphs have been supportive in reaching this decision.

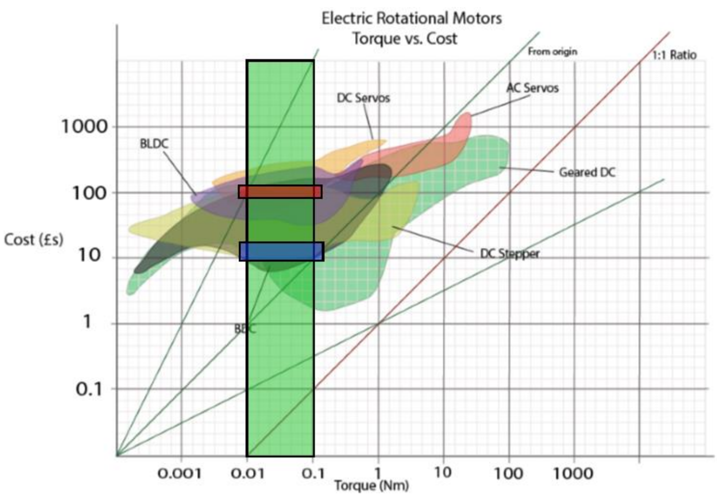

Figure 88: Comparison of motors in the range being considered, following on from the concept-level solution developed previously.

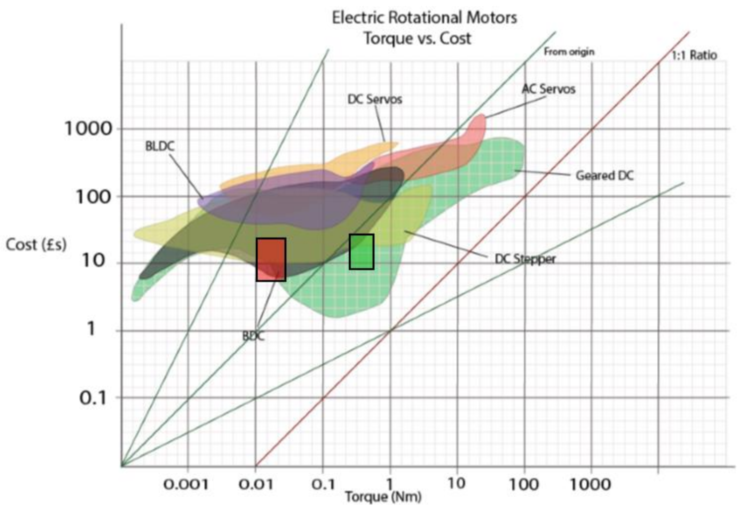

Figure 89: Cost options for motor selection. Options at direct drive given by black-bounded green box. Options driven through 10:1 - 50:1 gearing shown in green box bounded by red outline.

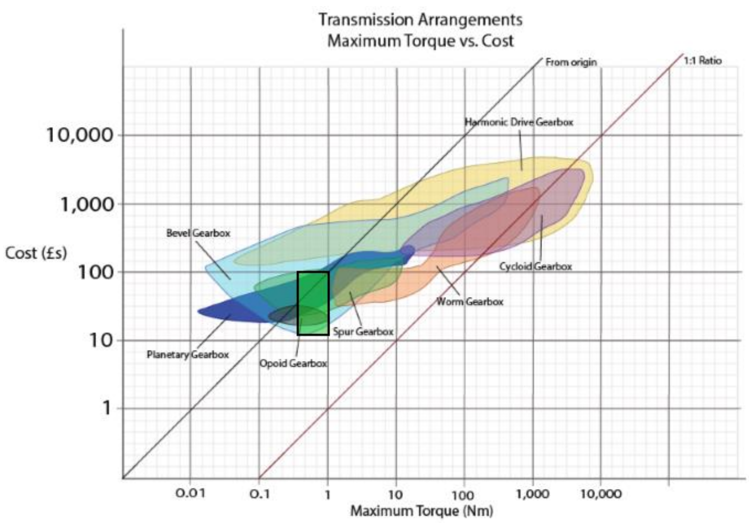

Figure 90: Overview of costs of transmission systems likely to be employed.

Table 32: Approximated cost comparison of direct drive and geared solutions. Best case and average case projections.

Approximate Costs	Direct Drive (average)	With Transmission (average)	Direct Drive (best case)	With Transmission (best case)
Motor	£50	£50	£10	£7
Transmission	£0	£50	£0	£20
TOTAL	£50	£100	£10	£27

Specific Motor Selection

Having followed the prescribed guidelines, an **RS Pro 191-8362 stepper motor** has been selected. Reference to other graphs have also shown that this motor runs at an acceptable voltage and is of reasonable mass for the application in mind.

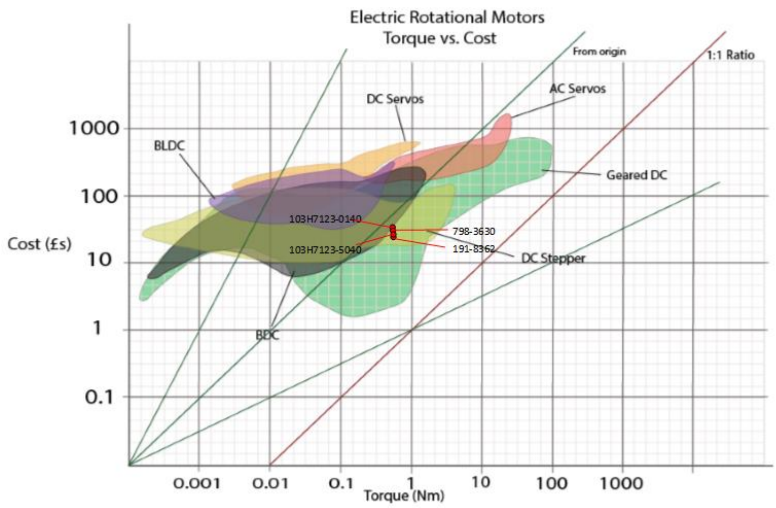

Figure 91: Torque plotted against Cost for motor selection. Specific instances of motors are shown graphically, enabling intuitive selection of appropriate motors based on key criteria.

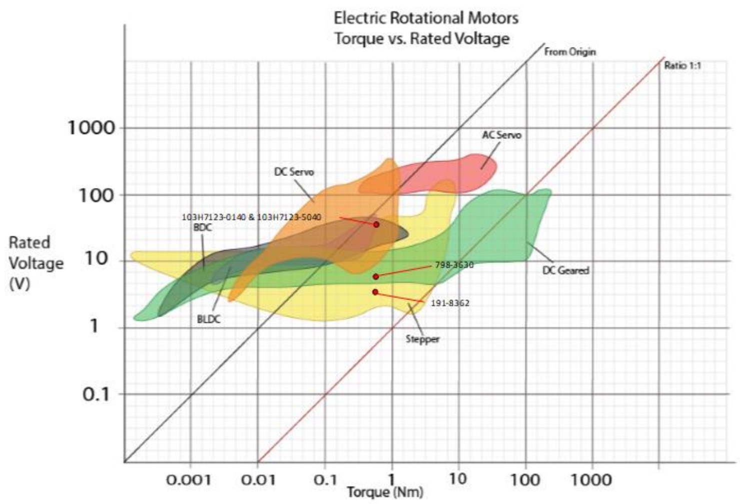

Figure 92: Torque plotted against Rated Voltage. Specific motors shown graphically.

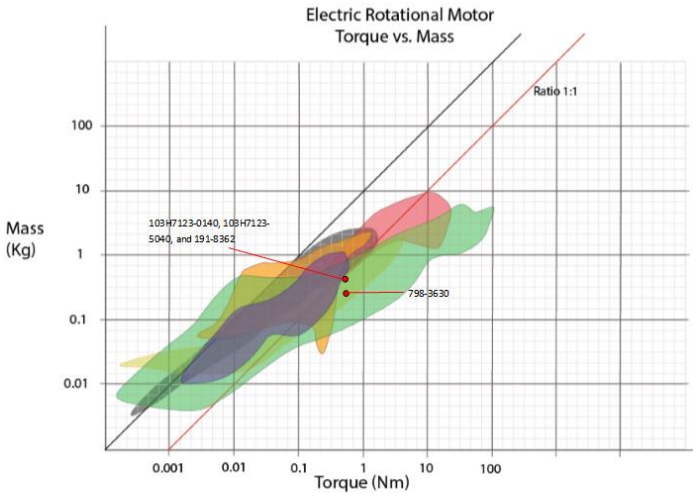

Figure 93: Torque plotted against Mass. Specific component instances plotted graphically.

4.3.1.4. Summary of Components Selected

Tables 33 and 34 provide an overview of the components which have been selected to be used in the developed system.

Table 33: Actuator 1 components utilised.

Actuator 1		
Component Type	**Manufacturer**	**Model**
Motor	RS Pro	191-8362
Transmission	N/A	N/A
Bearings	RS Pro	893-7424
Brakes	N/A	N/A

Table 34: Actuator 2 components utilised.

Actuator 2		
Component Type	**Manufacturer**	**Model**
Motor	Mellor	RS-550PH-6427F
Transmission	*Integrated solution*	*Integrated solution*
Bearings	SKF	624-2Z/C3
Brakes	N/A	N/A

4.3.2. Validation of Component and System Performance

Having utilised the framework to select components, it must be ensured that components selected perform as needed. Simulation of performance

Simulated testing of the solution has been completed, once again using V-REP. The system has been recreated exactly as it will be manufactured, with correct materials, masses, etc. assigned to elements in order to recreate accurate dynamic and friction conditions, and the system is set to perform as required.

As in previous instances, figure 94 demonstrates the movement of the end effector as applied by actuator 1. Given the machining application of actuator 2, this has not been possible to replicate in V-REP; however, is assessed in a physical test, as documented in the following section. Tables 35 and 36 show that all of the main requirements of the system have been met. The framework has been used from start to finish of the component selection procedure for a third time. Based on the simulated outputs of this task, it can be seen that the framework has, again, been successfully utilised to deliver a solution which meets the system requirements.

Table 35: Review of performance achieved in light of simulated testing. Actuator 1. Green highlight indicates achievement, grey indicates that assessment is not applicable, and orange indicates that assessment cannot be undertaken in MBD software

Criteria	Value
Power	0.103 W
Inertia	$\mathbf{5.56 \times 10^{-3}\ \boldsymbol{kg\, m^2}}$
Torque	0.588 Nm
Speed	5°/s = 1.6 RPM
Acceleration	$5°/s^2$

Table 36: Review of performance achieved in light of simulated testing. Actuator 2. Green highlight indicates achievement, and grey indicates that assessment is not applicable.

Criteria	Value
Power	0.016 kW
Torque	0.044 Nm
Speed	3,500 RPM
Inertia	$\mathbf{120 \times 10^{-9}\ \boldsymbol{kg\, m^2}}$

4.3.3. Physical Testing

As mentioned at the outset of this chapter, the hardware developed will be used in an automation and robotics demonstrator by the Advanced Forming Research Centre, with solutions developed so far used in ongoing projects. The end effector was manufactured as shown in figure 95. Regrettably, due to the Covid-19 pandemic across Europe and the rest of the world and the associated lockdown restrictions, it has not been possible to capture additional photographs to present here.

In testing the hardware, the same approaches as taken in case study 1 were adopted. Before progress was interrupted, the end effector had been trialled moving its own load through 180° arcs, as required.

This was also completed starting the motor from maximum extension, requiring the actuation package to overcome maximum torque and load inertia to manoeuvre. The physical tests have verified the results documented in tables 35 and 36 in terms of the performance capability of the developed EOAT.

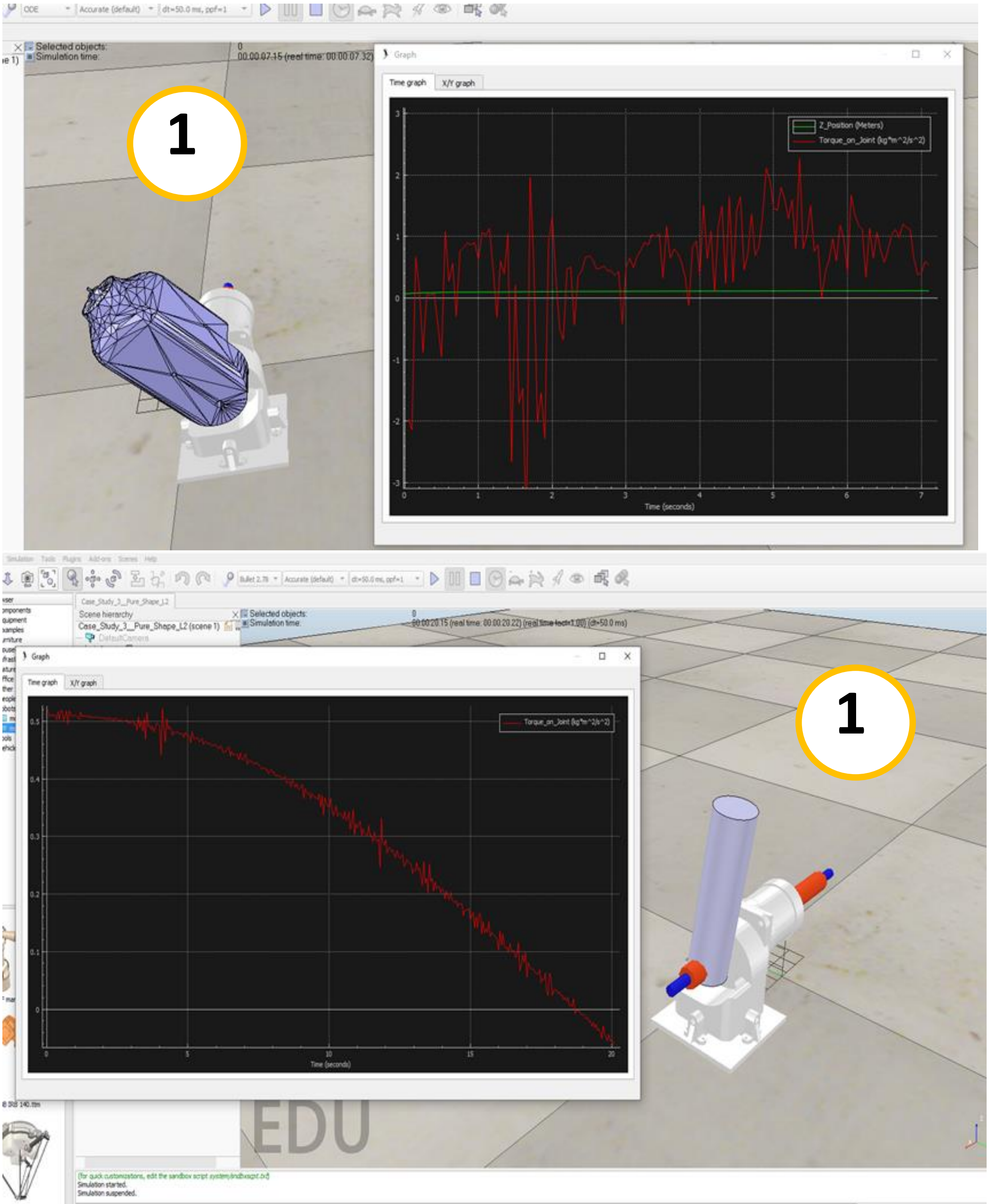

Figure 94: Simulated testing of joint 1 of the case study 3 solution.

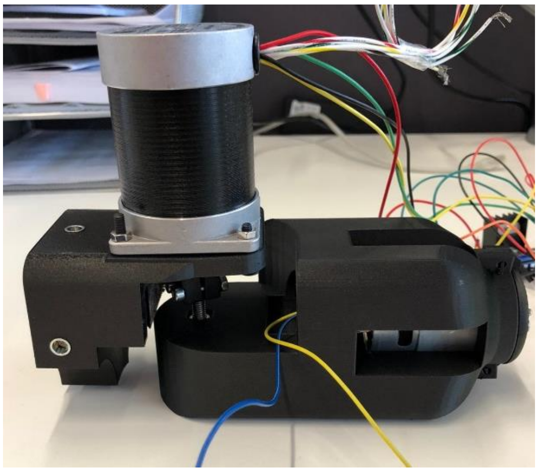

Figure 95: Physical end effector 1.

Actuator 2 has been trialled by coupling various cutting tools available onto the motor output shaft and attempting to cut through Styrofoam and balsa wood blocks, as required. This process has so far tested the process by changing cutting tools and varying motor speed in order to try and achieve a better quality of finished through the Styrofoam blocks. It has not been possible to document this photographically, as outlined already.

4.4. Absence of Expert Review

The approach taken to this study has been covered in detail in section 1.6. This section has clarified how the focus of this study, in line with the answers sought from the research question, hypotheses, and aim, must be on the application of the proposed methods and the overall framework. Only by doing so can it be ascertained whether the solution is capable of providing solutions which meet requirements. It is deemed that this is a necessary step as a step *prior* to involvement of other practitioners, as covered in section 1.6.2.

In the design of this research, the use of expert review had been explored; however, this is something which was decided against during research design for three key reasons:

1. At the time of research design, the researcher was not confident of accessing a cross-section of practitioners with strong enough background in this specific task within this specific use case that would enable true *expert* review to take place. This is an issue which has been compounded by the research project's resource limitations; i.e. not availability of budget to support involvement of such experts for the time required to review the work.

2. Given its novelty, the paramount concern of this work was ensuring that the framework (and in particular the component selection graphs) was actually able to produce results. As such, this is something which was prioritised. Authors of design research methodologies have commented

how all aspects of a study cannot always be completed "in depth in every single project" (Page 5, L. T. M. Blessing et al., 1998), so it was considered that a detailed study of application of this work was more valueable than less exhasutive case studies supplemented with expert review, particularly where, as outlined previously, there may be issues in finding several individuals with expertise in what is quite a specific task, given the use case.

Furthermore, by reducing the number of instances of *application* of the framework in case studies, and replacing these case studies with more involvement of stakeholders or experts, other issues may become evident. For example, if evaluation only covered one case study and a number of stakeholder reviews, the application case may *appear* to work well based on this one case study, and therefore stakeholders may corroborate this; however, as a result of less exhaustive evaluation, issues may be prevalent which have not been encountered since the single case study did not yield this insight. This is why literal replication has been sought, as per section 1.6.2., and is why 7 actuators have been developed with different requirements. Fundamentally, it had been considered that without a thorough application of the framework in the environment it is *designed to be applied in* (with some variation in the tasks it was applied to also introduced) there may be underlying issues not uncovered by less exhaustive studies. As per the outset of this point, since not all aspects of the work have been able to be completed in detail, stakeholder review has been reduced to facilitate increased case study-based assessment.

3. Finally, whilst this work is unique in what it delivers, the works which are *closest* to this work are all (Harmer et al., 1998) (Huber et al., 1997a) (Vogwell & Culley, 1991) (Zupan et al., 2002) (Madden & Filipozzi, 2005) (Cuttino et al., 2010) (Poole & Booker, 2011) observed to have taken the same route to evalute the work. That comparable works also have adopted this approach to assess their contributions forms part of the justification as to why a case study-based approach has been taken.

In addition to the above points, as mentioned, section 1.6. provides greater depth still as to the rationale taken in why a case study-based approach *has* been adopted, whilst this section has clarified the specific reasons why expert review *has not* been adopted in any significant manner.

The value of expert review is acknowledged, and interview of an individual with expertise in a niche aspect of this work has been undertaken in case study 1 as a means to provide some foundational input in this respect. The future value of expert review and larger scale user studies is explored further in this study, as per section 5.5.2.

5.0. Discussion

This section discusses the work contributed in this project as an overview (section 5.1.), in the context of existing solutions and relevant literature (section 5.2.), with respect to the project objectives and the design specification outlined in section 2.6.2. (section 5.3.), with reference to the project limitations (section 5.4.1.) and the framework limitations (section 5.4.2.), and, finally, with respect to proposed future work (section 5.5.).

5.1. Discussion and Review of the Framework – Overview

The work presented has analysed the effectiveness of a proposed framework for component selection and the novel methods it employs - of which component selection charts are clearly of foremost interest. The framework's operation has been detailed extensively through sections 3.1. to 3.3., before being summarised in section 3.4. Each of these separate elements are discussed in the same order in the following sections.

5.1.1. The Graphical Representation of Component Performance

The use of graphs has been shown to be valid and effective in aiding selection across a range of design challenges. At concept level they have been shown to be effective in shortlisting on numerous occasions (throughout chapter 4), with extension to 3D graphs also proving useful where applied, section 4.2.2. Testing of systems developed using this approach (4.1.5., 4.2.2.8., 4.3.2., and 4.3.3.) also show that the graphs have been utilised in developing functional solutions, evidencing their validity. With application, a range of lessons about the applicability of this approach have also been developed, as covered in the following sections.

Across section 3.1. and particularly throughout chapter 4, the understanding of how to use graphs has been developed and documented. It has been understood how graphs of the form proposed should be developed and augmented from criteria to criteria, and issues around creating certain graphs have also been elucidated. As well as in development, different graphs require a different approach to utilisation, and how they effectively permit rapidly shortlisting new component types when task requirements change (4.1.4. and others), evidencing the reflexivity of the graphs. Transmission graphs should be used in a different way to motor graphs, and concept-level graphs are used in a different way to embodiment-level graphs, for example. For the same component type, graphs can be used in different ways, depending on requirement. This process is now well-understood and has been evaluated in appropriate application scenarios. As a means to guide without constricting their use, guidance for graph use has also been presented as a process flow diagram to enable a step-based implementation which is intuitive and useful (appendix D.1.).

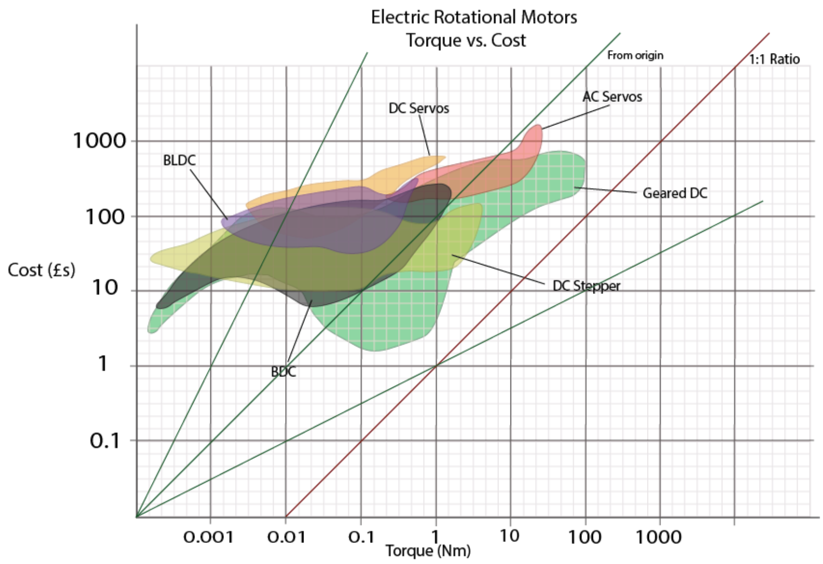

Figure 96: Example of component selection chart developed in this study.

With reference to figure 96, it has been explicated in much detail in chapter 3 and throughout case studies how the use of graphs allows intuitive interrogation of information to aid selections. Comparison between component types across a range of options and across a range of criteria is facilitated by graphs, also facilitating straightforward consideration of how changing gear ratios, for example, (and therefore facilitating adjustment of motor torque/speed). This and other traits which are quite unique to the proposed selection graphs are throughout. Graphs of the type shown illustrate the performance ranges of component types in a way which enables clear and intuitive comparison. No other works have been noted to have explored this phenomenon in the way proposed in this work, or in the detail expanded upon.

The process of graph compilation has also been documented, detailing the need for a comprehensive database (3.1.1.1.), the method of construction and representation the graphs are able to attain (3.1.1.2.), other nuanced information (3.1.1.). Having trialled their usage, these processes can also be viewed positively in delivering effective solutions, therefore, the approach used to contrive the graphs can also be viewed as correct.

In addition to general applicability, some features of graphs have also been shown to work well. Novel concepts such as 3D graphs have been evaluated (4.2.2.) with positive results (4.2.2.8.). Utilisation of graphs in concurrently assessing various criteria to define gear ratios has been discussed 4.2.2.2., suggesting a novel, more robust approach to definition of gear ratio - a typically trial and error-based task. Use of 3D graphs in normal cases has also been discussed at length, rendering working solutions, as demonstrated by extensive simulation (4.2.2.8., with further examples at PURE DOI). Issues have been highlighted surrounding how these graphs might transfer into practical use once a range of solutions are presented, section 4.2.3., subject to further evaluation.

The utility of indexing has also been evaluated in several instances throughout the thesis with no obvious issues encountered. Algorithms have also been developed to support where needed, and these have been evaluated with positive results, also developing understanding of the need to change approach depending on whether an X or Y criteria is being assessed. Means of applying these algorithms across varying graph types has also been proposed, as per section 3.1.1.3. Understanding of some of the quirks of using indexing with logarithmic scales has also been highlighted for awareness in future applications. In addition to indexing, it has been discussed throughout case study 2, section 4.2.2.1. how the "third face" of graphs allows clear intuitive representation of components which offer the best option across a range of criteria.

Other lesser expected benefits of graph use have been encountered too, such as their use to make assessments and averages on component masses, etc., as covered extensively in section 4.3.1., specifically tables 31 and 32. It has also been noted how effectiveness of methods like this can be expected to become more and more useful when dealing with a more comprehensive database. Using graphs allows comparison of averages (and other) criteria without the need to change filters/re-search, as would be required in existing solutions. This process has been shown to be very helpful, and accurately depicted the best and average cases for actuator 1 and actuator 2's development in case study 3. This facilitated examination of probable prices to be expected within performance ranges.

The graphs aimed to assist in mitigating the 4 issues outlined on page 52, as well as other issues outlined throughout this thesis. These issues expand on those also captured by the requirements list presented in section 2.6.2., which is addressed more directly in section 5.3.2.

As per appendix C.3,, on occasion components are sought but none are available. Graphical representation has assisted in observing the most proximal *available* solutions as a substitute for consideration. Existing platforms like dropdown menus, etc. are quite poor in this regard. The graphical method allows a means of easily ascertaining where the "next best" solution is. Remedial action is needed to address problems such as that detailed in C.3., with this provided in section 5.5.1.

As with other aspects of the work proposed, there is room for further development, with specific suggestions provided in section 5.5. Attention can therefore be turned to developing mechanisms to make *application of the principles* a more straightforward and intuitive process.

Broadly, the graphs have shown effectiveness in concept-level application by allowing rapid assessment of quantitative information of components, and also comparison against other options available. It may be necessary at some stage in the selection task to move towards a more traditional "cataloguing" manner of displaying components once initial shortlisting using graphs has been undertaken, since high volumes of components may make the graphs difficult to read. This needs to be trialled in a study with a more comprehensive database, as noted in section 5.5.3.

It has been noted throughout this project that a lack of standardisation and incorrect representation of component information in existing platforms is common. It is proposed that this graphical method provides a means to counter this through intuitive representation of component information, and eventually by providing more straightforward unit conversion operations. The graphical approach proposed has shown promise in its use as a means to select a range of component types.

5.1.2. The Hierarchical Taxonomy Structure and Qualitative Reference Information

5.1.2.1. Taxonomy

The hierarchical taxonomy attempts to develop understanding of the interactions between components utilised in mechatronic systems, in answer to various points captured in the requirements list specified in section 2.6.2. It has explored a new means to present qualitative information to an user. Appendix B.4. outlines the qualitative databases relied upon through each level. Similarly, appendix B.3., provides the hierarchical taxonomy which correlates to the database headings used. A high-level taxonomy has also been created, relying on information gained throughout chapter 2; figure 97, below. This strong basis on existing literature is corroborates to some extent this developed outline. A hierarchical taxonomy of the nature provided has not been encountered through literature covered (section 2.4.), and it is considered to constitute a foundation of categorised information utilised in actuator development.

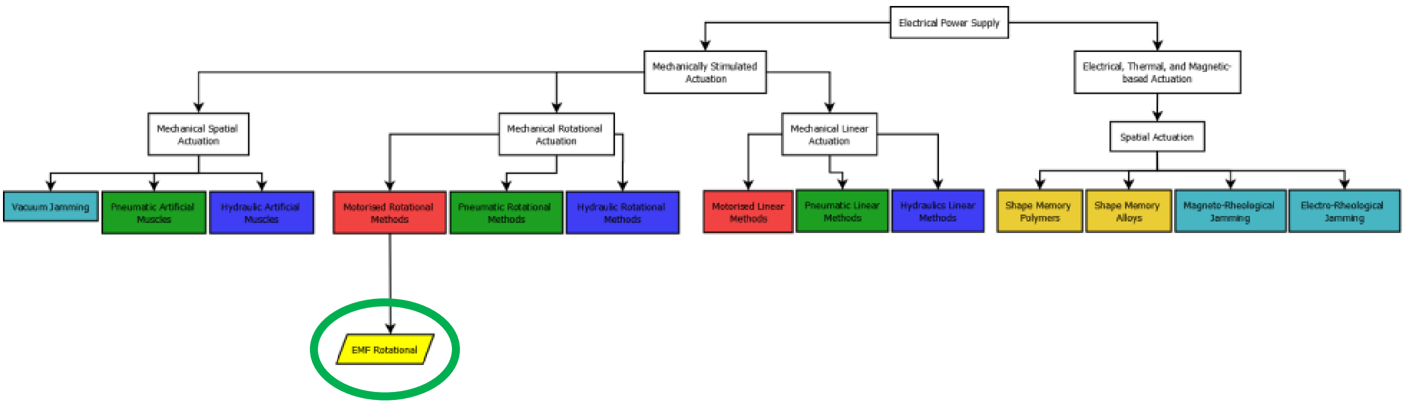

Figure 97: High-level hierarchical taxonomy of actuator technologies.

As alluded to in figure 97, categorisation in this study has focused on components utilised in systems driven by electric rotational motors, highlighted in green circle. Appendix B.3. provides more comprehensive breakdown at the next level, where component types are categorised more fully. From this, many of these components supporting the drive mechanism can be applied to other "motorised rotational methods" of drive. This has facilitated understanding of the component types which work best together, which is not observed to have been mapped out formally before, based on review of literature.

A major driver to develop this hierarchical structure, is to aid definition of the headings which should be used for qualitative databases. Hierarchical taxonomy supports this across a range of granularities, and is discussed as important across a range of literature, as described in section 2.4. The taxonomy allows to rapid communication of component relationships, and clarifies headings used in interrogation of qualitative overviews of component capabilities. Together, they form part of a solution which enables cognition of candidate solutions which may otherwise have been overlooked. Future study should include expert review on *this element* of the work to corroborate the composition of the taxonomy proposed.

5.1.2.2. Qualitative Databases

The qualitative databases which provide overview of traits of component types have been shown to be useful in flagging qualitative issues with prospective components; detailed throughout section 4.1. for a *single* actuator at *concept*-level, with numerous other allusions throughout this thesis. More detailed discussion on this can be found at PURE DOI. Qualitative inputs through the proposed manner have been demonstrated to provide input informing system development in a positive manner. The information they provide would normally require research to ascertain, or would be based on engineers' significant experience. This has helped to address points of the requirements list from section 2.6.2.; discussed further in section 5.3.1.

In developing the databank of qualitative information on components, the researcher had to use innumerable sources, ranging from core textbooks on mechanical design (Childs, 2003) (Collins et al., 2010) and mechatronic design (D. Bradley & Russell, 2010) (D. A. Bradley et al., 1993) (Billingsley, 2006), specific component handbooks (Hughes, 2013b) (McCoy, 1996) (Ewert, 1997), and a large range of manufacturers' catalogues and documentation. The issues encountered in developing *this* framework and its methods serve as evidence of the difficulty and time-consuming nature of attaining information in component selection *generally*. Finding and developing understanding of information is often a difficult task, which is something this proposed solutions specifically seeks to address. This serves as further evidence of the potential utility of a single, central and *comprehensive* database of this type of information, particularly if enabled with tools to make its interrogation as effective as possible, as proposed based on section 2.6.2..

An **eventual** solution is envisioned to perform like the examples discussed in figure 45 much earlier in this thesis. Form application in this work, it is noted that enabling access to qualitative information alongside the graphical kingdoms in an eventual solution is considered to be of greater utility later in design tasks. In an eventual software architecture, this would allow the user to reference quantitative information, filter using this information, then quickly switch to qualitative review of components facilitated by graphs. This adjustment is accounted for in an amended framework structure discussed in figure 101, in section 5.1.4.

The data represented in qualitative databases must also be more exhaustively completed to increase the effectiveness further. At this stage, the approach has demonstrated capability in positively affecting system development tasks at a proof of concept level. The application of this tool has been sensible, but further development is required to enable this system's use in a larger range of "real life" applications. It has been observed to provide an intuitive method to quickly assess qualitative information about types of components it considers. Its potential use as a learning tool is also pointed out, and a paper on this subject was accepted for the Engineering and Product Design Education 2019 conference, demonstrating some consensus on this proposition.

5.1.3. The Guidelines

The step-wise guidelines developed as part of this framework have been iterated through 3 intensive applications in case studies. These developments can be reviewed in more detail at PURE DOI, whilst the final guidelines are presented in figure 99 and 100. Throughout these developments, the guidelines have been augmented in order to capture greater detail as considered relevant during application processes. The guidelines have also been developed in order to interact with other tools utilised in this framework, although it is considered that other tools could be used in their stead with the guidelines maintaining their efficacy. This development process has facilitated understanding of how the guidelines operate and what is necessary to enable them best. This has included assessment alongside other guidelines/methodologies (section 4.2.), which has shown significant overlap with the underlying logic of both.

Both sets of guidelines have received adjustments. Boundaries have been imposed to group information related to a specific process. At concept level two new steps have been added: **Step 1** now dictates that the framework may be consulted in development of solution working principles, an outcome to case study 2; **Step 4** recommends sub-system requirements are developed to enable targeted component selection tailored to these requirements. In embodiment guidelines: **Step 4** recommends that component types are reduce component types prior to selection of an individual *instance*; **Step 9** suggests that selected components be integrated into the sub-system and assessed for ability to meet requirements.

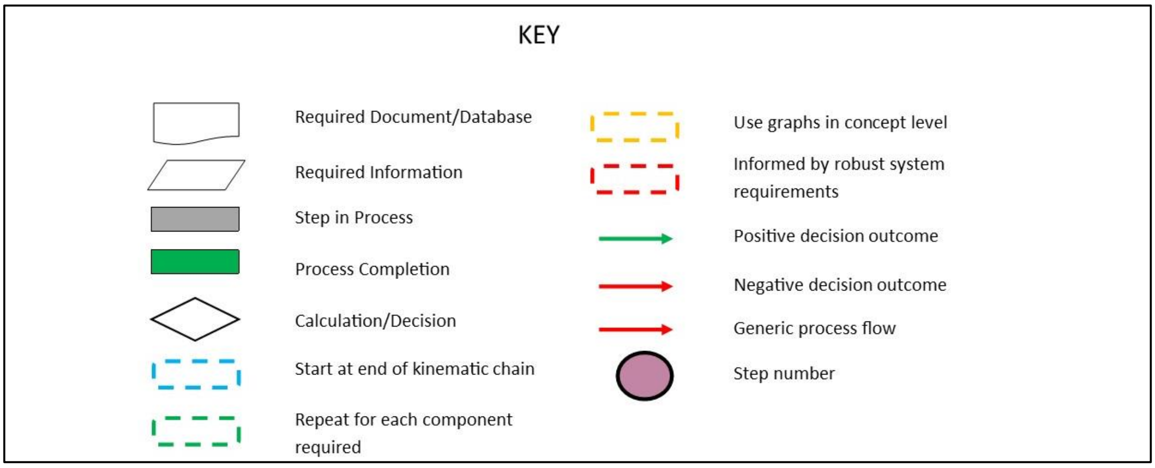

Figure 98: Revised key for revised component selection strategies.

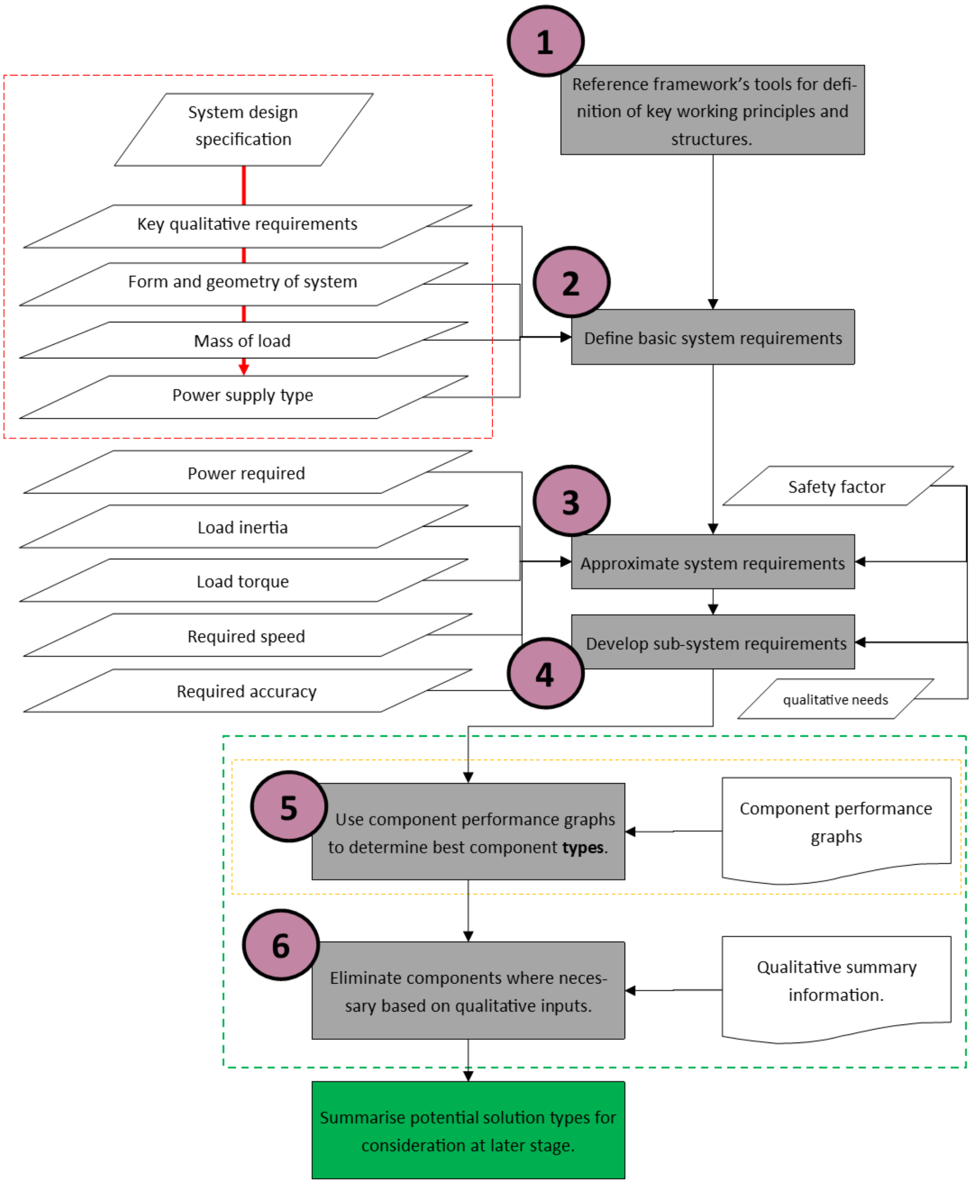

Figure 99: Final concept-level guidelines.

The guidelines attempt to account for interdependencies between components in a system, whilst also accounting for the effects of components *on one another*. Motor and transmission are clearly linked, but the mass of bearings on the torque output required, etc. is also worth noting, particularly as it relates to various actuators throughout the entire kinematic chain. The guidelines have established a logical and robust approach to tasks of this nature. Guidelines for use of graphs are purposefully high-level and are considered to provide all the information necessary at that level needed. Clearly the step-wise guidance is also unique to this work, given the unique nature of the graphs developed and also the overall framework.

The guidelines have been shown to support component selection for development of capable actuation solutions to meet specified requirements throughout this thesis. A potential problem lies in guidelines potentially changing for different component types in future application; however, this is not a concern of this research owing to the previously imposed research boundaries enabling proof of concept assessment within this project. Graphs and qualitative data use should be universally applicable, whilst guidelines may require redevelopment to include new components and to account for niche applications. In future work, there may be utility in exploring generalising these guidelines to a greater extent, or a "toolbox" of a variety of guidelines.

It has also been explored during case studies that guidelines need not be adhered to religiously: deviation from guidelines is encouraged where the engineers' knowledge of the problem dictates need to do so. Guidelines in this thesis extend specifically to use within this framework, though it is considered that these same guidelines could be used more generally. This may also be an avenue for future work to review.

5.1.3.1. Use of Analytic Hierarchy Process

One of the most noteworthy attributes of the guidelines proposed is inclusion of the Analytic Hierarchy Process to form ordered precedence for component selection. This has been trialled for embodiment design of every actuator developed in this thesis, with a raft of examples throughout case studies and specific instances covered in appendix C.2.1. This information proved valid and correct in the first instance, and has been utilised to inform and guide robust selection of component in order to find components which best meet the *system* needs. Guidelines dictate development of and reference to design specifications throughout, and embodiment guidelines specifically ask for AHP as an input which pulls from requirements to define precedence, before delivering precedence to inform downstream processes.

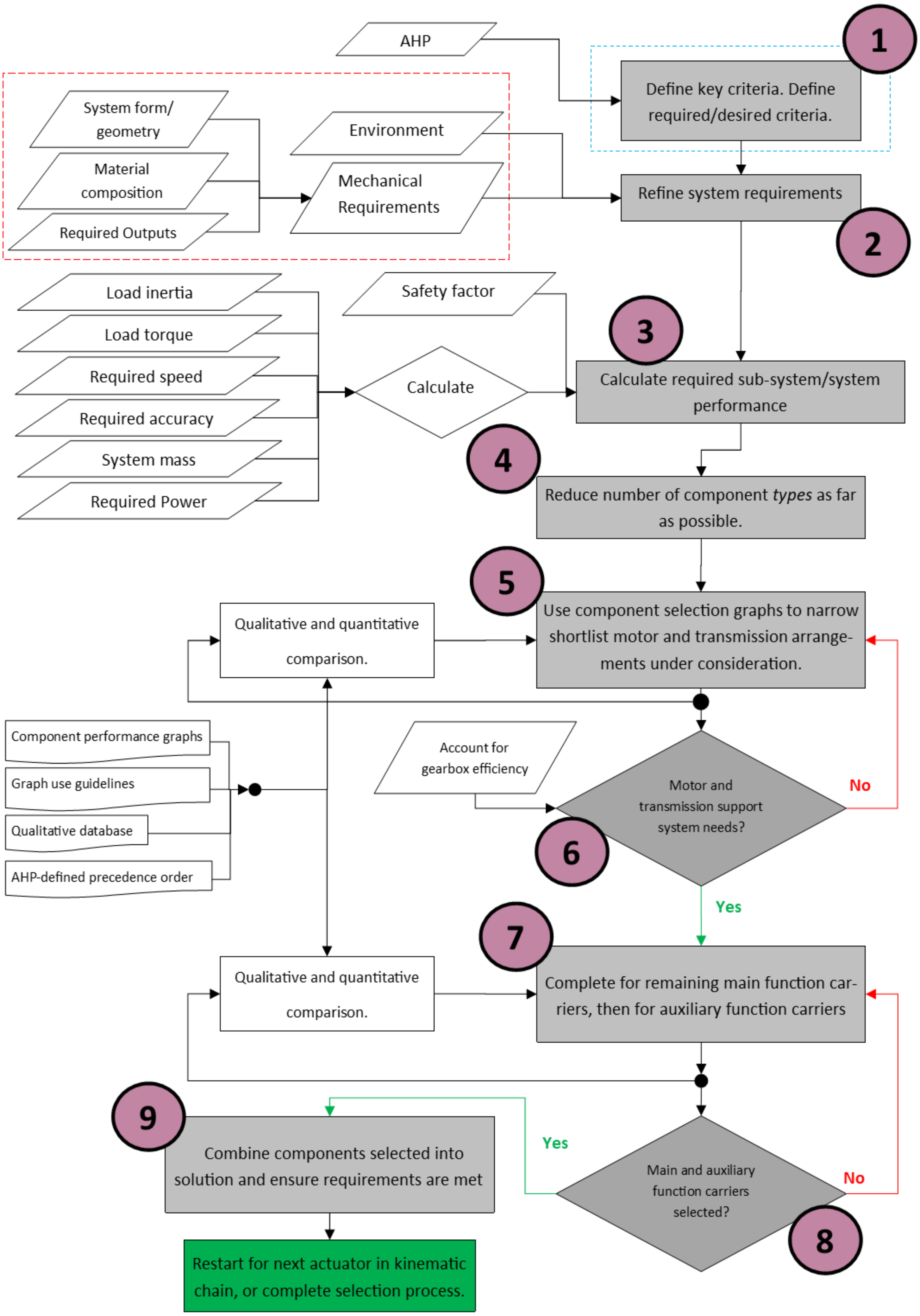

Figure 100: Final embodiment-level guidelines. Refer to key presented with figure 99.

AHP has been utilised in developing functional solutions, also suggesting the merit of its inclusion. Whilst discussing this content at conference, it had also been remarked upon as a useful feature of this work, evidencing the research community's value of it. Post-case study 3 changes encourage definition of required and desired criteria on the back of AHP inputs, utilising weighting as a means to inform this definition process. Prior to this work, component importance is only observed to have been developed *ad hoc*, without any systematic approach.

AHP has shown great promise in allowing precedence of component criteria to be considered, allowing selection to be structured and targeted around the most pertinent requirements. This has allowed tailored selection for each component to the task for which it is intended – affording the guidelines excellent adaptability from case to case.

5.1.4. The Framework

The framework overall has been shown to support component selection by producing a range of valid and effective solutions in component selection tasks. All but one actuator operated without issue, with some mitigating circumstances surrounding operation here, as detailed in section 4.1.5.2., and corroborated in section 4.1.6.4. Requirements were shown to be met in all applications where the framework was applied, and in a benchmarked process the outputs were shown to have significant improvements over the previous solution, as highlighted in table 37, below, though actual impact is arguably larger than this suggests.

Table 37: Comparison with existing design in case study 1 application of framework.

Criteria	Previous Total	New Total	Percentage saving
Mass	3.067 kg	2.483 kg	19.1%
Power	252.8 W	48.2 W	81%
Cost	£1,255.18	£762.01	39.3%

There was an acknowledged issue in this case study as well, though the issue encountered appeared to be something of an ongoing issue as discussed in section 4.1.6.4. through interview:

> *[In joint 1] "There is also a manufacturing problem, the worm and the wheel are not in close contact. They should be closer together to have better behaviour from the system."*

Section 4.1.6.4. provided a host of additional qualitative information on how some approaches are currently taken, and highlighted a range of issues surrounding how the engineers themselves acknowledged that their component selection process rendered solutions which did not meet speed and mass requirements:

"This joint should perform a bit faster, I think. When we did it, it was not as performant as we wanted. I don't think this system would be able to do the task it was asked."

This same engineer suggested that had a solution of the nature proposed been available then it would have been helpful in their efforts, as evidenced through several answers provided in section 4.1.6.4. In particular, graphs were highlighted as one area which would have been expected to be helpful. So, in addition to showing quantitatively that an effective solution has been developed, approval has been gained by an engineer working on the initial system. Generally speaking, the main concerns from existing approaches tend to be overreliance on certain platforms for selection, lack of guidance at crucial stages of the process, and complexity in selection. Through the process and the tools suggested by this work, it is considered that this proposed solutions has laid foundation to resolve these issues to a large extent. These same issues are remarked upon throughout research.

Understanding of how the framework operates within itself and with external elements has also been developed. In chapter 3, section 3.4., an overview of how elements of the framework were expected to relate to one another was presented, with an updated version of this presented in figure 101 after iterations of testing. Various changes have also been made to *sub-elements* (i.e. application of graphs, etc.) of the framework, as discussed in previous sections. This has improved understanding of how the framework and its supporting elements function. The overall framework structure, as presented in figure 101, has remained largely unchanged, with the exception of a change suggesting that the qualitative information should be accessible through the graphical interface as well as through the hierarchical taxonomy.

There has also been an extensive development of understanding surrounding how the system interacts with other design strategies. Figures 78 and 79, present well-refined understanding of the stages in a design process at which the framework is of greatest utility, with reference to a seminal design methodology. The specifics of applying the framework as an embedded tool within a design methodology have allowed corroboration across a range of aspects of *this* framework, whilst also introducing considerations of other elements which the framework previously did not account for but now does: this process is documented throughout the entirety of section 4.2. Through this process, a range of understanding has been developed surrounding the framework and its tools' applicability to the development of systems, and, crucially, when they are best applied. This has been a useful learning point, and of key significance relative to the potential utility of the framework as a learning tool for students, etc. There have been many examples throughout chapter 4 where all elements of the approach work in concert to deliver a solution which meets requirements: AHP defined priority, allowing guidelines and graphs to be used to good effect in definition of best components to use. This has extended to use in gear ratio definition and other upsides not directly intended during development, evidencing great applicability and versatility.

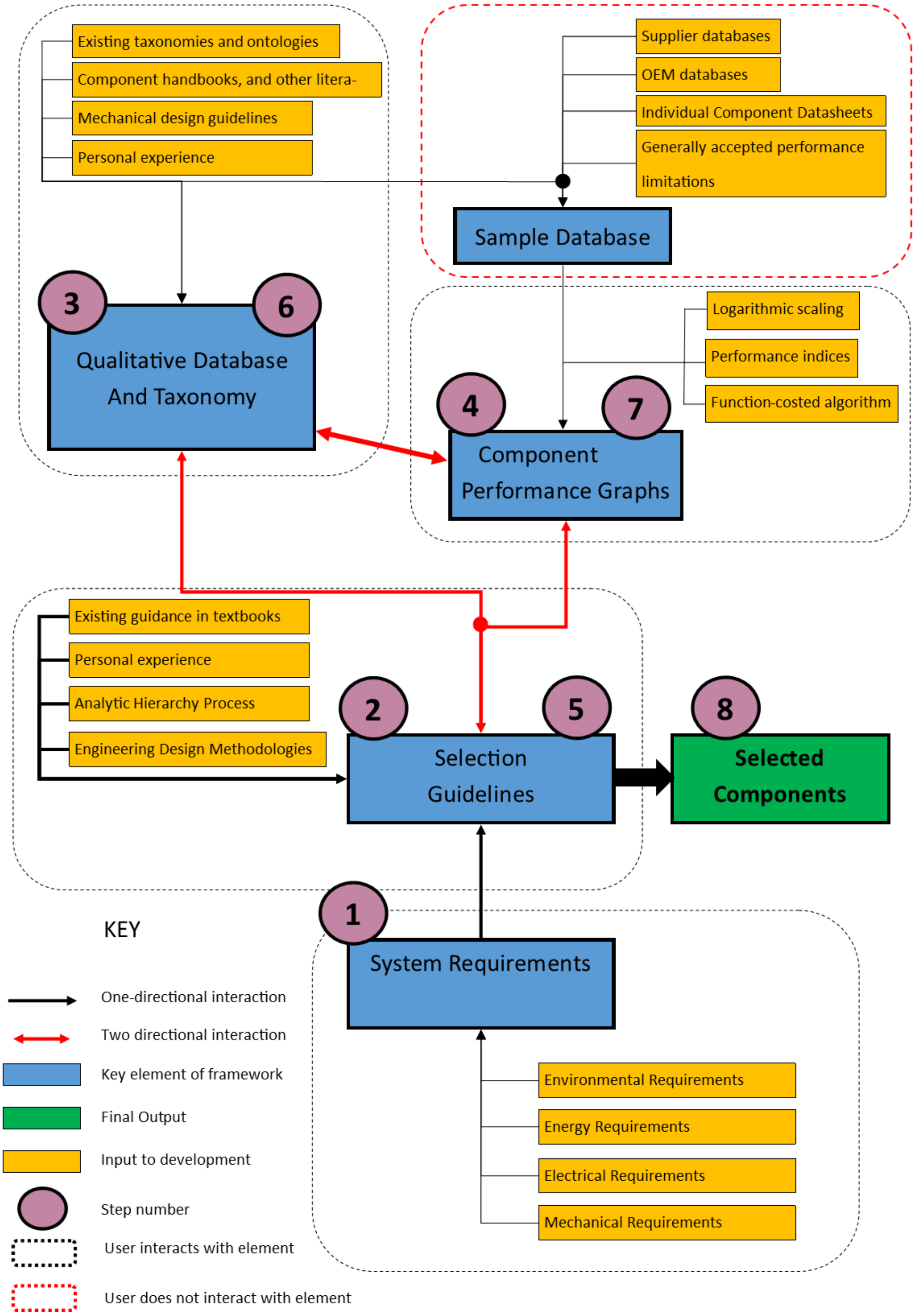

Figure 101: Revised version of framework interaction. Note heavy green line demonstrating that the information in "interactive taxonomy" should also be accessible from graphs.

The framework has been shown to be versatile in adapting to different design challenges, and changes within a design process from concept development level through to specification of a specific component instance to address a specific system requirement. This is evidenced by all three case studies and the outputs which have been validated as functional solutions. It has also shown capability in design of a (very) simple "machining tool", as per section 4.3.3., further evidencing this point on adaptability and versatility.

Earlier in this thesis throughout chapter 3, the issues encountered in developing this framework have been remarked upon. Absence of a platform for comparing a range of solutions in an intuitive manner is a problem, but the lack of access to key data on engineering components is a problem generally. It is considered that by showing that the framework has proven valid in enabling solutions to be created, this solution shows promise in helping to resolve both of these issues with further development, assuming OEMs' data is able to be accessed to compile a central database.

Application has provided a very robust understanding of how the framework is to be utilised in-situ. This study has shown how the framework can be effective in ways not expected, and has explicated the exact nature of how it operates as applied. Use of the selection graphs, in particular, have allowed quick decisions to be made. This is a point that should not be understated. Component selection is a necessary task in engineering, but it can be a time-consuming and non-value adding task – it is postulated that this is why it is often referenced without greater detail in mechatronics design methodologies, as per section 2.1. It can be time consuming, but if not completed successfully it can *detract* value from a system or cause delays in project completion, which adds cost (Siddiqi et al., 2011)S. Aiding the process to be completed more quickly and more effectively is therefore a desirable and worthwhile outcome. The proposed framework has been shown to support these outcomes in a positive fashion. That the framework has been shown to support it *effectively* in terms of the results produced is very encouraging.

In addition to the framework operating well in the environment for which it was intended, it is proposed that the approach developed provides an excellent starting point for educating engineers, as it formalises and clarifies much in terms of the decision-making processes in component selection, and also the relationships between technologies and entities. This, hopefully, allows more straightforward understanding of the manner in which these components are likely to be used.

5.2. Discussion and Review of the Developed Framework in the Context of Existing Works

The justification for taking on this project has already been outlined. Various comments and key points have been made throughout this thesis, with particular, concentrated argument made in section 2.6., where the gap and the specified requirements are clearly described.

5.2.1. From literature

Beginning at the highest levels of fidelity, an array of seminal texts in mechatronics, robotics, and mechanical engineering provide very broad overview of how selection should be achieved for various components. Instances are encountered where selection is summarised, almost dismissively:

> "Select the actuators and their mechanical transmissions for the operation conditions adopted at the outset" (page 400, Angeles & Park, 2016)

Such approaches are not uncommon (Bolton, 2015) (Siciliano & Khatib, 2016) on component selection and similar themes (Bietz, 2007) (Hubka, 1988). Others do refer specifically to component selection (P. Hehenberger et al., 2010) (I. Graessler et al., 2018), and acknowledge the steps involved (Salem, 2014) (Kernschmidt et al., 2018) (Zante & Yan, 2010) (Gausemeier & Moehringer, 2002b), but do not go as far as specifying an approach to resolve in a robust manner. Literature review section 2.1. has highlighted how a vast array of mechatronics methodologies, models, and frameworks acknowledge the significance of the task without providing (or deferring) to any method of implementation. Strategies and formalised methodologies which have been specifically developed to support component selection have been explored in detail, as per section 2.5.1. This enabled a clear understanding of the existing guidance which is available for consultation to promote clear steps to approach this task.

A quite limited number of solutions are encountered in literature, whilst solutions found are noted to lack detail and specificity as to the guidance they provide. The guidance presented in this thesis is argued to evidence far greater effectiveness of supporting selection throughout the two phases (Cebon & Ashby, 1997) of selection than existing strategies employed. The framework and its underpinning guidelines specify clearly the steps to be taken, the type of information which should be considered, and has also developed a several tools tailored to assist this *specific* task. Despite their differences in granularity, many of the existing strategies encountered do outline similar thematic concerns relating to the process, which corroborate this framework's logical operation. This has also been shown throughout case study 2, where this framework's guidance has been shown to overlap heavily with Pahl and Beitz's **general** approach – albeit, again, at a far different level of granularity.

Strategies are proposed by Vogwell and Culley (1991), whilst step-based guidance of merit is also noted by others (Cuttino et al., 2010) (Poole & Booker, 2011) (Culley & Webber, 1992b) (Carlson, 1996), though specifics are also absent in many of these cases. That is not to say other approaches are not specific, some are encountered which are very application specific (Zeraoulia et al., 2010) (Meoni & Carricato, 2018) or seek to optimise for one particular parameter (Hicks et al., 2002) (Esen et al., 2016) (Agarwal et al., 2007). Almost all still casually refer to use of supplier/manufacturer's available solutions and platforms, which have their own issues, as outlined throughout chapter 2. Many parallels are found in problems with component selection in software applications, and some inspiration has been drawn from frameworks (Konys, 2015) and models (Verma & Mehlawat, 2017) in this arena, which propose tangential ideas to those explored in this work. The fact that these approaches are accepted in other fields verifies the validity of considering MCDM, models, and frameworks as a means to address selection problems.

From literature, little support is presented on databases to interrogate, the type of information to interrogate, prioritisation of most relevant criteria, etc. This is noted throughout section 2.5.1., and has informed definition of knowledge gaps and the requirements list presented in sections 2.6.1. and 2.6.2., respectively. In answer to this elucidated concern, an overall framework structure has been developed to support the links between key tools to be referenced in selection. One of these key "tools" is the selection guidelines, which provide clear, step-based points of how the selection process should be completed and what type of information should be reviewed. The framework proposed facilitates implementation of a tailored solution to assist this process to an extent not found in existing literature.

The guidelines in this thesis deal with selection in more detail for a specific application, including tools not available to any earlier noted works. This markedly differentiates this work. It is also clear that where similarity exists in terms of the idea of graphical representation (Harmer et al., 1998) (Weaver & Ashby, 1996) (Zupan et al., 2002), the vastly different interpretation of this method of representation applied in this thesis, the depth of exploration, the accompanying guidelines, and the use case and difference in systems represented add up to a substantially different proposition. Existing representations applied to actuator-related components suffer from smaller sample sizes (Zupan et al., 2002) or use of line or dot-based representations (Huber et al., 1997b) (Madden & Filipozzi, 2005) (Poole & Booker, 2011), which have limited capability in the information they provide, and do not support selection beyond initial "screening". It is noted that none have explored selection of specific component instances, neither have they explored use of graphs across a *range* of component types. This work is proposed as a first iteration of a more universal solution, which explores all granularity from concept through to specification of a single component instance. There are also very idiosyncratic elements of this work (algorithms governing index use and use of AHP processes to guide selection) which make this work truly unique in the context of other related works.

Various complementary works on categorisation (Peter Hehenberger, 2015) (appendix A.3.) and taxonomy (Nilsson et al., 2009) (Schlenoff et al., 2012) (Prestes et al., 2013), whilst others have considered classification of components as part of system design processes (Peter Hehenberger, 2012) (Jones et al., 2017) (Sharpe & Centre, 1995) (Peter Hehenberger, 2015). The importance of taxonomy has been highlighted (Cebon & Ashby, 1997), and has therefore been explored in this work as discussed throughout 3.2.1.

Aside from direct comparison with other strategies for selection, a number of other works have also been helpful in compiling this work. Analytic hierarchy process has been utilised, though existing comparison with other MCDM methods available (Jahan et al., 2011) enabled this selection to be justified. Equally, the value of exploring indices has been shown in materials selection (Weaver & Ashby, 1996) (Ashby, 2005) with good effectiveness, which has helped justify exploring their potential utility in this instance.

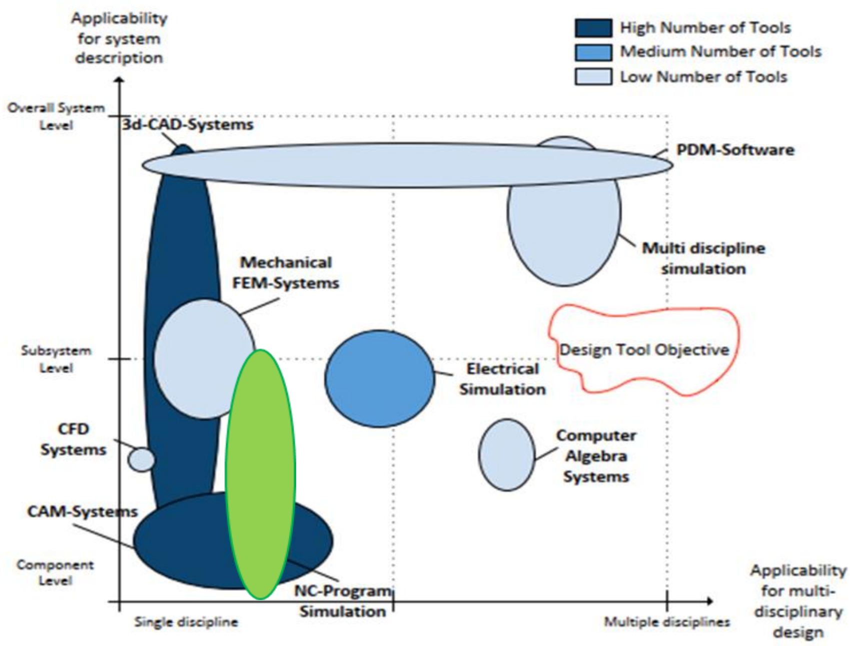

Figure 102: Where the work is considered to sit in application, highlighted in green. (Peter Hehenberger, 2012), *green highlight added*.

As a final point in the context of literature, it is considered that figure 102 outlines where this proposed tool could sit in the scheme of other design tools and approaches used in mechatronic system design, as defined by other research (Peter Hehenberger, 2015). On the Y-axis, it is proposed that this tool should enable selection of a range of components from specific individual components all the way through to "subsystem" type components. Whilst it may be useful in *forming* an overall system, it does not support beyond selection of components. On the X-axis, it is considered that this tool should have application across a broader range than some existing methods, as its utility has already been demonstrated across a range of application cases. It is, however, not considered to be a multiple discipline tool on its own; it can be used for component selection for different component types, as a learning aid, as a means to outline useful component types, as a reference tool, amongst other uses, but there it is not considered to possess enough functionality to be considered multi-disciplinary. It is considered to perform in a region of the graph in figure 102 where no existing technologies exist at the moment.

5.2.2. From industry

In addition to review of existing literature, solutions developed and provided by OEMs, *which are not covered in formal scientific literature,* has also been included in review. Section 2.5.1.1. deals with this head on, introducing the solutions encountered at the project outset. These have consisted mainly of drop-down menu selection approaches and a few better, and more detailed methods. The key differences are the tools utilised in this approach, and this framework provides systematic guidance alongside things rather than, often, a complicated or unintuitive UI. The work presented here is also not manufacturer or component specific.

During the process of this work at least one other selection solution is considered to have been released which performs well (Hampshire, 2020), but is also not without issues. Beckhoff's selector provides a similar interface to that produced by Oriental Motors, but provides a new interface for showing components available comprising a traffic light system, shown figure 103. The left side of the image shows performance for a *single* motor, whilst the right side lists motors available. The green line envelopes nominal torque from motor, wilst red line envelopes instantaneous torque capacity available from the motor. Red arrow denotes **required** nominal torque, and blue arrow indicates maximum instantaneous torque the system **required**.

On the right side, only information on torque, speed, inertia matching, etc. are conveyed. The software does not facilitate comparison across a range of other criteria, and there is no known means to review generic qualitative data either, which separates it from this work. A very useful feature of this software is that it automatically suggests components which work well together to provide the performance needed, which is something this thesis has also discussed, in section 5.5.1. Beckhoff currently extend this platform to only their products, which consists of a limited range of product types. This thesis envisages capturing a larger range of component types, across a larger range of criteria, and using a different interface to show *multiple* solutions on the same graphs, allowing simpler comparisons.

Figure 103: Beckhoff Automation selection interface.

The solutions devised by of Oriental Motors and Beckhoff are very useful and effective in representing component performance – more so than other interfaces encountered. That OM and Beckhoff have *recently developed* this solution clearly shows that “drop down” menu type solutions are not perceived as the future, further solidifying the arguments of this thesis. Industry leaders in automation have reinvented their approach to component selection evidencing the value of graphically-based, intuitive selection approaches being of utility. They have not achieved this in the same way as this work, or for the same application. It is considered that these solutions are extremely effective in very particular applications, whilst this work is developing something to be more universally applicable.

Beckhoff and OM’s solutions are useful at different stages to this framework, and omits guidelines, etc. These platforms are considered a good *complementary* software, rather than a “competing” approach, achieving something different than this work seeks to. Some elements, especially around definition of component requirements are considered to be excellent additions that this work would greatly benefit from inclusion of as tools; specifically, automated calculation of requirements.

A system like this would be incredibly useful as a “plug-in” at the front end of this work, particularly in embodiment level. It is observed that a worthwhile overall “vision” would be to draw information directly from CAD design assemblies to automatically generate actuator requirements, then provide an interface for selection based on these parameters. This information could then be fed back in to inform amendment of parametric models and facilitate cyclic revision until a solution is met. Use of other novel ideas such as traffic lighting may also be useful at this point. OM/Beckhoff’s solutions differ from this work in that they are only applicable at a very specific point in the process of design; i.e. when all figures are resolutely known. These systems also suffer in the same way as others: applies only to certain components; applies only to the OEM’s catalogue of components; cost involved in using the software; etc.

Generally selection platforms in industry are drop down menus, which require a lot of trial and error to find the information sought. One is often searching for components without knowing there is no solution; e.g. an engineer seeks a best solution of a motor with 1 Nm torque and of length 0.03 m, but they will not know until after a drop-down search is complete that a solution does not exist at 1 Nm with length 0.03 m, for example. Quickly referencing the graphs would allow definition of *where* the "next best" solution is available. Graphs facilitate immediate observation of where the next best solution is. This is a crucial benefit of the graphs, which support decision making in a more time effective and solution effective manner, in addition to supporting effective and efficient selection outright.

5.2.3. Summary of Overlap with Existing Content

Literature shows a constant theme evidencing work in system configuration and component selection being undertaken, as does recent innovation in selection developments. When comparing with the content already available, it has been shown that the proposed approach is different. The guidelines in this work are specific to use of tools developed in this work, therefore knowledge of how they are applied and the tools themselves are unique to this research. Knowledge developed around AHP application and use of indices is also unique to this work, as is application in this use case.

There are points of overlap with existing literature, as documented in section 5.2.1. This has allowed comparison of the slight differences, and has also allowed discussion of elements of other works which would be extremely useful additions to this work. This is supplementary to much of the work outlined in section 5.5. surrounding proposed future developments. Thematically, the literature on the subject highlights many of the issues identified in this work, in terms of supporting the need to define the task and requirements clearly; however, beyond that point it is found that literature often lacks the specificity that this work provides and that there are many elements unique to this work in terms of tools developed in this thesis.

It has been demonstrated that this work varies greatly from industrial/commercial solutions, and it has also been evidenced that it is unique from literature which is currently known. The direct use and applicability of this work has been shown to be justified through discussion in literature, and implicitly through the abundance of solutions in this area. Many indirect possible use cases are also noted, coinciding with taxonomies (Dudek et al., 1996) (Korsah et al., 2013) and ontologies (Fiorini et al., 2014) (Schlenoff et al., 2012) (Haidegger et al., 2013).

5.3. Developed Framework with Reference to the Project Objectives and the Specified Solution Requirements

Analysis in this section is devoted also discussion around the extent to which the requirements brief has been met, section 5.3.1., and to discussion of the extent to which objectives of the project have been met, section 5.3.2.

5.3.1. Relative to Requirements List

Table 38: Requirements list developed to prescribe the necessary traits of an effective component selection solution.

Scott Brady Ph.D. Thesis	Requirements list for a component selection solution in engineering design activities	09/08/2020
D/W	**Requirements**	**Responsible**
D	**Support conveyance of quantitative component information to users:**	SB
D	- Compile database of quantitative information on component types of interest to this study;	
D	- Establish a method to support interrogation of this information;	
W	- Establish a method to support intuitive review and comparison between prospective solutions in component selection activity; and,	
D	- Support process through to selection of individual specific component, based on quantitative performance parameters.	
D	**Support conveyance of qualitative information to users:**	SB
D	- Compile database of relevant information on the component considered;	
W	- Capture information from high-level to moderate level. Individual component datasheets can provide specific component-by-component qualitative information;	
D	- Provide a mechanism to support interrogation of this qualitative information; and,	
D	- Provide a format for display/conveyance of relevant information on component types to the user;	
D	**Provide a baseline categorisation for components considered**	SB
D	- Define the categorisation of components to enable representation of qualitative and quantitative information; and,	
W	- Build on previous work to develop up to date and logical taxonomies of components relevant to the selection procedure being developed.	
D	**Support decision-making:**	SB
W	- Provide users with spectrum of information available such that decision-making is supported by allowing review of all relevant information; and,	
W	- Where definition of most important parameters is required, provide robust and formalised means of determining criteria precedence	
W	**Support selection with respect to other components**:	SB
W	- Selection of components impacts the selection of other components. This interaction should be accounted for and supported in any guidance provided	
D	**Overall guidance through component selection task completion:**	SB
W	- A solution should build upon previous process flow diagrams and step-wise guidance;	
D	- The user's attention should be drawn directly to the most important information required in selection tasks; and,	
D	- This design specification has already prescribed the need to explore novel solutions to communicate information. An overall strategy to clearly specify the interactions and steps to take is necessary.	

The requirements of table 4 are duplicated in table 37, above, for ease of reference. Of these requirements, it is considered that each have been met:

- **Quantitative** information review has been supported through implementation of graphical representation (presented in 3.1. and discussed in 5.1.1.).
- **Qualitative** review has been supported through qualitative databases as a proposed solution for general component types (section 3.2.2.), whilst the specifics of individual component information should be sought from individual datasheets unless a database which also captures this information can be proposed. Review provided in section 5.1.2.
- **Taxonomy** developed as per section 3.2.1. has supported establishment of a foundation for further work in this domain. Review provided in section 5.1.2.
- **Supporting decision making** is achieved throughout the use of the guidance provided (section 3.3.), and at varying levels (3.3.1. and 3.3.2.). It has already been reviewed in section 5.1.3.
- **Selection with respect to other components** is an aspect of the developed system which has been built into the selection guidelines developed, as outlined in the previous point.
- **Overall guidance** throughout the selection task is supported by all previous elements discussed in the points above, and also covered from section 3.1. to 3.3. Section 3.4. brings these key elements together to provide a synergistic solution. This is discussed throughout section 5.1., but is summarised in 5.1.4.

5.3.2. Relative to Objectives

In section 1.3.1., objectives have been developed in support of ensuring that the project aim could be delivered and the research question answered. These objectives can now be discussed in the context of the extent of their completion. Five objectives have previously been discussed, as per section 1.3.1. Their delivery is now discussed, as follows.

5.3.1.1. Objective 1: Develop understanding of state of the art in the context of the subject matter; i.e. state of the art in robotic actuation, mechatronic design methodologies, and component selection strategies, methods, and tools.

Extensive literature review has taken place pertinent to understanding relevant up to date and state of the art in robotic systems, actuation systems, and component utilisation. Whilst not directly significant in terms of the contribution of this work, this review has been critical in developing a foundation of understanding of the technologies to be considered throughout this thesis, despite not being central to the contribution eventually delivered.

Mechatronic design methodologies, the selection process, and specific methods, strategies, and tools employed in component selection are entirely central to the contribution delivered, so have been discussed in detail throughout chapter 2, whilst the outputs of this process have served as clear evidence which has been utilised to guide and document the development of this work through the remainder of the thesis

5.3.1.2. Objective 2: Develop specification of traits that an effective solution for supporting component election must possess.

A key output following the completion of objective 1 has been the delivery of a requirements list of what the work put forward should attain. This has been achieved through 2 key outputs of the review. Most poignantly, the design requirements list for the solution to be delivered has been specified and discussed in detail in section 2.6.2. This document has been outlined clearly in this section, and has provided a target for the solution to be developed, which is subsequently discussed in chapter 3.

Whilst the requirements list has been the central deliverable in answer to this objective, it has been critically underpinned by other milestones. In section 2.3. a structured approach to review was determined based on the findings from initial exploratory review of "higher level" content which was perceived to be significant to the contribution eventually put forward. The structured set of criteria has been important in targeted assessment of literature discussed throughout the remainder of chapter 2, which enabled clarification of opportunities to develop useful new knowledge.

5.3.1.3. Objective 3: On the basis of the specified requirements, develop a solution to meet these requirements;

Chapter 3 has been dedicated to the development and delivery of a solution proposed to address all of the issues identified from literature review and compiled into the requirements list delivered in section 2.6.2.

This addresses "development" of the solution, whilst meeting the requirements has been dealt with extensively in discussion in section 5.3.1., where the exact nature of the solution's capacity to meet each point of the requirements have been discussed in detail. Section 5.3.1. has outlined how the proposed solution has performed strongly in terms of addressing each of the points raised by the design requirements list.

5.3.1.4. Objective 4: Expose the solution to typical use cases in order to assess its functionality as applied in these typical situations such that the effectiveness of the solution can begin to be understood.

Throughout chapter 4, the solution proposed in chapter 3 has been exposed to a variable range of design scenarios through which it has been evaluated and iterated. This process has served as a useful mechanism to ascertain the extent to which the framework has been able to deliver functioning solutions, in line with the overall requirements of the project.

In addition to facilitating gathering of information to aid answer of the overall research question, case studies have also provided the pathway to enable detailed understanding of how the framework and its underlying methods perform *as applied* in design scenarios. This has aided clarification of how to apply them (throughout sections 4.1., 4.2., and 4.3.), specification of where in engineering design tasks they should best be relied upon (section 4.2.), and a variety of other information which has provided unique, new knowledge.

5.3.1.5. Objective 5: Analyse development and application of proposed solution to provide clear assessment of the effectiveness of the solution in delivering functional systems.

Following evaluation of the framework developed as the "solution" to the problems identified and documented earlier in this thesis, the key learnings have been able to be documented and discussed. Whilst this analysis and assessment has, in part, begun during chapter 4 with specific discussion on elements of the work *as it was being undertaken*, chapter 5 and 6 provide a clear and regimented discourse on the work provided and the effects of it.

This ranges from discussion around the extent to which the research aim has been delivered on (section 6.1.), provision of an answer to the research question (section 6.2.), general overall discussion of the framework and its underpinning elements (throughout section 5.1.), discussion of the framework in the context of existing literature (section 5.2.1.) and available solutions (section 5.2.2.). This discussion also extends beyond what the framework has achieved and its capability, and discusses the limitations of the framework (section 5.4.2.), as well as the potential limitations of this study as it has been implemented, the lessons learned, and things which could be addressed (section 5.4.1.).

As final points which supplement discussion of achievements and limitation of the work, discourse is also presented around the significance of the contribution (section 6.4.1.), application in future design practice and how the work can be leveraged already (section 4.4.), and a more general array of recommendations for future work which would assist in building an even more effective solution, with this work as a strong foundation (section 5.5.).

5.3.5. Summary

It can be seen from section 5.3.2. that a methodical approach derived from the defined research approach has been taken to tackling each of the research objectives, and that these objectives have demonstrably been addressed throughout this thesis. Answers have been provided as to the extent to which each of the objectives have been met, and it is considered that they have almost universally been met through a robust process where there is typically more than one element supporting completion of any objective. This evidences the integrity of the research and its outcomes, and it also serves to justify the claim that the objectives have been achieved.

5.4. Limitations

Limitations of this work are discussed under two headings. Firstly, general project limitations are outlined and discussed, followed by discussion of the specific limitations of the framework and its associated methods.

5.4.1. General Project Limitations

5.4.1.1. Unable to Physically Test Novel Actuator in Case Study 2

As dealt with in chapter 4, section 4.2.2.8., it has not been possible to physically develop the system for testing in case study 2 due to the budgetary limitations of the project.

There therefore exists a minor concern that the ability to verify that the system works in a physical setting is compromised. Corroboration of simulation by physical testing in other case studies does, however, evidence that this system would also be *expected* to function as required. To counteract this, more exhaustive simulation has taken place for case study 2, whilst parameters of the system have also been tested to failure as well. It has been shown that the system should be capable of actuating loads more difficult than those in this task.

5.4.1.2. The Use Case

The framework proposed has so far primarily only been trialled for mechatronic actuator development for robotic systems. This does not evaluate approaches to different systems, therefore assessment of this in future works may be advisable. The step-wise guidelines are quite specific to actuator development for robotics systems, so may not transfer to vastly different systems; however, use of the other tools should be largely transferrable – this would be interesting to investigate, but was also outside the scope of this work.

5.4.1.3. Further Development of Hierarchical Taxonomy Structure and Qualitative Databanks

The hierarchical structure is expected to require further development to make it more exhaustive. This is a limitation which has been necessary to assess the work to the extent required; however, a by-product of this is that issues which may be encountered at greater depth have not been able to be registered and dealt with. This is also out of scope for this project. With the induction of a software package to support application of the proposed framework, taxonomy reference may become more streamlined and qualitative databanks can be more readily accessed and maintained.

5.4.1.4. Usability by Others

Only with development and then user testing of the framework and its associated methods in a software platform can assessment of how users unfamiliar with this (i.e. not the author) utilise and understand it take place. The work conducted in this thesis has shown the framework capable of producing solutions to meet system requirements, and allowed assessments of its effectiveness in delivering these solution, which has been the key interest of this work.

Understanding how users unfamiliar with this novel framework interact with it would also be useful, but will require a separate study. It has not been an interest of this work, as outlined in section 1.6., etc. Concerns around this have also been robustly addressed throughout section 1.6., and also directly in section 4.4. As commented previously, action research has been discussed to follow "advancement of practice" (Page 127, Kumar, 2014) - therefore future studies should look to explore these themes.

5.4.1.5. Researcher's Involvement in the Process

Given the goals of the research study, it has been necessary that the researcher be the individual to implement the application of the framework and its supporting aspects, as documented in section 1.6.2. The work presented in this work is unique to this work, therefore training of others in the use of the tool has not been practical or feasible within the resources of this project.

Despite best efforts to ensure that the work presented is free of bias, there may be instances where unintentional bias has affected documentation of the results gained. Similar biases could, however, also make their way into action research studies owing to how interviews, responses, and observations are interpreted. Only by ongoing study across changing parameters can bias truly be reduced.

5.4.2. Limitations of Framework and its Associated Methods

Whilst section 5.4.1. has covered project-specific issues, this section clarifies what are perceived to be the existing limitations of the framework in terms of how it is able to be applied.

5.4.2.1. Limits of the Components and Criteria Assessed

Section 1.5. imposed clear limitations on the boundary of the research, whilst chapter 3 also supplemented this with boundaries applied to criteria to be considered, etc. It has been outlined how it is necessary to consider a limited number of components, and for those components only a limited number of criteria should be considered; enough to enable proof of concept. These are necessary boundaries, without which the task would be inordinately difficult and expansive, making its completion extremely difficult to attain within this project's resource, but also difficult to measure.

The more components and criteria represented, the more flexibility and utility the framework provides. This limitation has inhibited assessment of the framework to some extent – that is, it has inhibited assessment at a higher level of development, but this is not what has been sought through this exercise. This exercise looked to establish whether the framework was allowed solutions to be developed which met system requirements, and the depth provided has facilitated this assessment. The next logical step would be to expand this work to consider further components and criteria.

5.4.2.2. Limitation of Guidelines Transferability

The guidelines relied upon are reasonably specific to the use case undertaken in this work. As such, the guidelines are particular to the development of drive chain component selection in mechatronic actuators, as outlined earlier in section 1.5. Therefore uncertainty exists surrounding the extent to which guidelines will be of utility as applied in other instances, which is something future work may wish to address.

5.4.2.3. Usability of Certain Component Selection Graphs

It has been discussed, particularly in section 4.2., how 3D graphs can be quite difficult to interpret, and that with a greater range of data presented this format may become even more difficult to interrogate. By extension, with truly comprehensive capture of available components, 2D graphs may also become difficult to interpret; however, this is not known at this stage and must be explored in further study.

This work has encountered some issues in this regard already in 3D graphs, but also in 2D graphs. As well as identifying the issue, means of resolving this problem have also been put forward, section 5.5.1.

5.4.2.4. Access to Information Needed to Develop Graphical Representations

Since depiction of components to be selected is dependent on having knowledge of the criteria relevant to make these depictions, access to this information is critical. As outlined in prior chapters, certain criteria is often difficult to attain since not all manufacturers provide, for example, mass information. Similarly, it has been found that when trying to develop graphs for certain components this can also be tricky, sensors has been previously cited as one example of this, as covered in section 3.1.1.2.

Application of this method requires that information is available to be utilised in the proposed manner. Many manufacturers provide all data needed to support this, whilst others are less forth coming. This has been noticed to be particularly evident with higher end components, where *quotes* are often required to attain prices, rather than unit costs being made available up front. This potentially presents an obstacle to application in such instances.

5.5. Discussion and Review of Suggested Future Developments

Part of contributing to knowledge entails opening up avenues to other researchers to complete new work. This is something this work has achieved extensively, and some key recommendations of next steps are able to be made as a result of this.

These recommendations are the author’s suggestions based on extensively familiarity with the work, except where stated otherwise.

5.5.1. Software Package to Support Application

A software package to supply more intuitive and usable selection is considered an obvious next step for further development of this work. Completion of this goal would open up avenues for various types of research exploitation, and after instantiation of some initial platform further expansion to add greater capability based on feedback from case studies and user trials would be advised. The theory of the framework has been demonstrated in this work, but with greater numbers of components and criteria, software becomes essential to aid in a task of this nature.

The use of software is anticipated to increase utility as far as the ease and speed of review of applicable content, as alluded to throughout this thesis. Issues with displaying on a log graph have been identified, which software may aid resolution of. As higher orders of magnitude are reached, it becomes harder to detail exactly where a component lies on X and Y axes. The issue and a potential solution are well-described in figure 104 would be of great assistance in this particular application.

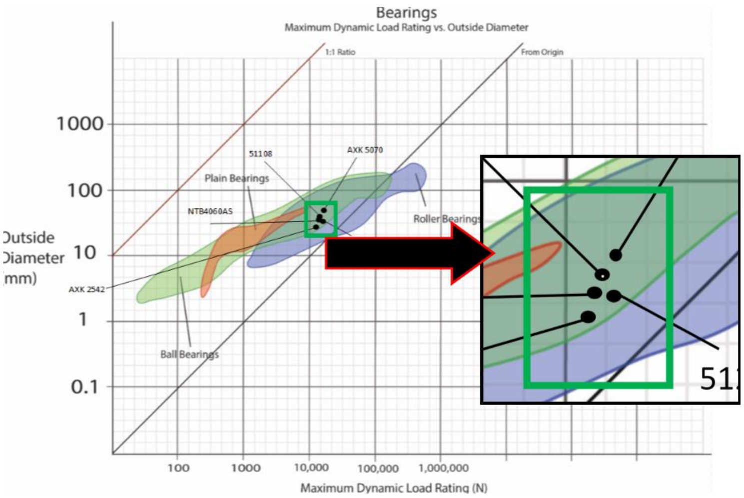

Figure 104: A software platform should facilitate expansion of areas of interest in graphs, such that information of interest can be more easily reviewed and useful components identified.

Use of AHP and the prioritisation of criteria is also a very manual process which software can part-automate. This opens avenues to facilitate better identification of required or desired criteria, allowing future work in terms of development of more increments on this scale; i.e. not just desired/required, but “required – priority 1”, “required – priority 2”, “desired – priority 1”, etc. Incorporating algorithms developed to allow indexes of motors to be automatically displayed would also be advisable and useful. Automated suggestion of component types which work well together for certain application, is another area of study that this work lays foundations for. Something similar is utilised by Beckhoff

Automation's motor selection system, discussed in section 5.2.2., but only extends to trialling gearhead and motor combinations. With reference to the Pahl and Beitz quote in this same section, there is also scope for the framework to assist in populating and enacting *existing* tools used in system design. This is also another avenue which this work has opened up for further research.

A software package could also be utilised to highlight regions where components do not exist, but are frequently sought by engineers/customers. Instances in this thesis have been found where components were sought but were not available; appendix C.3. Clearly, this has been due graphs only representing a sample at this stage, but the utility of analysing where users are searching for components is demonstrated in figure 105. If users are frequently searching for solutions that do not exist, this information can be used to inform where solutions should be developed, as highlighted in red. "Shading" of regions to show density of components in that area would also be useful; i.e. light green areas of the "class" mean there is only few solutions there, whilst a dark green region suggests high density of solutions in that region. The basic idea of this is highlighted in blue boxed region, figure 105.

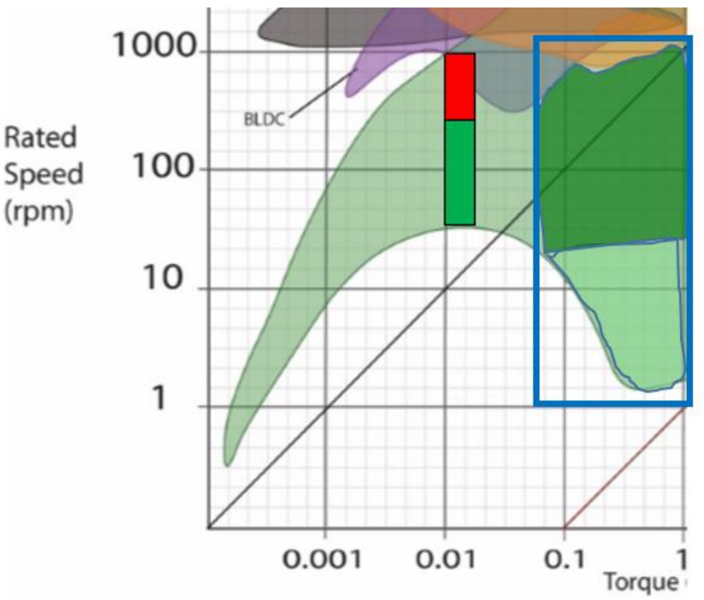

Figure 105: Issues in graphs during selection and proposed measures to address these problems.

5.5.2. User Trials

The study completed in this thesis has focused purely on ascertaining the validity, and strengths and weaknesses of the developed framework for delivering solutions to system requirements.

It would be useful to understand elements of the system which are most helpful, and elements which are still laden with issues *whilst users interact with it*. This will promote further understanding of the process, and encourage refinement towards a better end solution which, crucially, is usable for engineers.

In addition to trials being of utility in developing the framework produced, it would also be useful to run comparative trials. It would be useful to understand in more detail how the approach compares to existing approaches by understanding user experiences of both, allowing statistical data to be produced to support future development. This will enable strengthening of the framework and its tools, addition of new tools to suit requirement, and possible removal of certain aspects of this proposed work which are not considered useful by users.

5.5.3. Exhaustive Collection of Component Performance for Representation

Compiling and representing a far more exhaustive list of components and criteria is the step required to achieve this. Based on applications so far, there are no recognised impedances to extending this approach of criteria representation to other criteria.

Comprehensive representation of component performance opens doors to a range of new research, including:

- Studies like this, performed with more criteria and a larger database, enabling learning at deeper levels of granularity;
- Studies on different system types to assess the framework's efficacy in designing electric cars, washing machines, etc., yielding knowledge of idiosyncratic elements of system design which the proposed framework does not lend itself to well; and,
- Studies where the framework is applied to selection of components for a different application to those in this study. For example, selection of components for PCBs, or pressurised systems (oil and gas, etc.), facilitating learning of how transferrable the approach is.

Graphs should be extended to consider more components, a broader range of components, and more criteria. New features, such as shaded regions discussed in figure 105, and breakdown of components at even greater granularity – for example, represented BDC motors by those which are wound in series or shunt, etc. – should also be explored. Whilst this study has considered many hundreds of components to provide a robust overview of the components available, it is necessary that the next developments of this work are even more comprehensive in nature. The more comprehensive the database for interrogation is the better quality results can be expected

5.5.4. Collating 3D graphs across all component types

It would be useful to have 3D graphs for transmission too. Utilising 3D graphs for other components would allow further learning to be developed. Exploration of these graphs as applied in a software environment would also be useful in determining whether this platform can enable these graphs to be of even greater utility.

5.5.5. Provide Method to Automatically Generate Graphs

The framework relies heavily upon the novel, graph-based method of interrogating information. One of the major drawbacks at this stage is that those graphs need to be produced in quite a manual fashion. Development of a system to automatically produce graphs tailored to particular criteria would be enormously helpful.

6.0. Conclusions

Answers to the project aim, research question, and broader comment on the contributions developed in this thesis are provided herein.

6.1. The Project Aim

The project's aim provided in section 1.2.1. has been:

> **To develop a solution to support methodical completion of component selection tasks when designing mechatronic actuators for use in robot sub-systems.**

The project aim has outlined the need for a solution to aid component selection. Following review of relevant literature and existing solutions, a framework and supporting methods have been proposed as the answer to this solution. Development through this thesis has sought to provide a valid and effective means of selecting components in a methodical fashion. The following sections will discuss broadly the extent to which the framework is valid, and how effective it is, thus, answering whether the project aim has been met.

6.1.2. Has the Aim Been Reached?

In answering whether the aim has been reached, it is important to consider the constituent elements of the aim. In this case, it is considered that these elements are:

1. "develop a solution"; and
2. Support completion of selection for design of actuators.

6.1.2.1. Develop a Solution

This point has been covered extensively in chapter 3, with discussion in section 5.1. Discussion provided throughout chapter 4 have also contributed to development of aspects of the framework through iteration. Sections 2.1. – 2.5. make a clear case for the need for the solution, whilst section 2.6. specifies the requirements of the solution. Chapter 3 has detailed the framework proposed, and its development. This aspect of the aim has been met owing to the depth of information conveyed throughout this work, but particularly in these referenced sections.

6.1.2.2. Support completion of selection for design of actuators

Throughout chapter 4 it has been shown that the framework proposed is able to support the selection of components when designing actuators. Design and testing of seven actuators has been completed and, in all but one scenario, the actuators worked as intended, with this one scenario evidencing circumstances which affected the design outcome, as per 4.1.6.4. In this failed case, it is considered that the same problems could have been met whilst using a different approach to component selection, which was partly corroborated by interview in section 4.1.6.4.

The framework has been applied to a range of solutions, with varying applications. Successful cases in this thesis are abundant, showing the framework to have been valid in producing functional solutions to meet requirements. Not only has the framework been applied to robot system design, but having applied it to a *wide range* of elements of robotic systems, it has been a thorough application of the framework in this field.

Having established that the ability of the framework to provide solutions, how *effective it is in doing so* can be discussed. To assess its effectiveness the interest is on *how well* it achieves an intended goal. Despite clarification of the need for component selection aids from 2.1. and 2.2., very few existing solutions are encountered, as discussed in section 2.5. and analysed in section 5.2.1.

Results of case study 1 showed a valid solution able to meet system requirements, and delivered a lighter, cheaper, more efficient system; see table 37. Case study 2 has outlined how the framework relates to existing methods, summarised in 4.3.2. Throughout case study 2 the framework was shown effective in communicating the right information at the right time, as verified by comparison with literature. Case study 3 assessed the approach in designing a system for an industry application. The results of application have shown that the approach is effective, as discussed above, but application by the researcher has also allowed assessment of how it is effective and in which scenarios.

It has also been demonstrated that the systems are able to manoeuvre loads in excess of what they would be required to manoeuvre, faster than required. They are not able to do so far in excess of what is required, which is considered a positive, as this suggests that the components are specified correctly, rather than being far more capable than is necessary; they achieve roughly what would be expected plus their defined factor of safety. FoS used in this thesis has not been extensive (typically 25-50% larger than needed), which shows the framework has selected components within a tight margin in terms of required minimum and additionally specified FoS. This further reinforces the argument that the approach is effective.

In addition to straight comparison of *outputs* produced, the effectiveness can be measured in the tools utilised to produce outputs. Performance indices and criteria precedence through AHP have proven to be valid and effective mechanisms for approaching selection in a rigorous and systematic manner, demonstrating effectiveness of *aspects* of the approach as well as the overall approach. AHP in particular has proved very effective in allowed a precedence of operations to be created in component selection. That these element add value independently and work cohesively towards an end product is very pleasing to see.

All of this is to say that the framework is effective in guiding the process. Graphs have been shown to promote rapid assessment of quantitative performance of components, and an intuitive and easily interpreted interface. It has also been shown to be capable of producing results of a good standard, and which compare favourably to systems designed using other approaches; case study 1. With further development, the approach is expected to be yet more effective.

6.2. Answering the Research Question

The objectives and sub-points discussed in chapter 5 were formed to support and work towards answering the research question. The research question is provided below, to reiterate:

> **How effective is the proposed solution in supporting methodical component selection to facilitate selection of components to meet functional system requirements?**

By this point, much of the justification already provided across chapter 5 and chapter 6 has made many of the points required to answer whether the research question has been addressed. To avoid unnecessarily lengthy discussion on this, these previously provided answered will be heavily referenced throughout this section.

The term "proposed solution" has been used at the outset so as not to pre-suppose the solution of the project, which has been a framework. The framework needed to be established and assessed with regard to how effective it is in use. Section 6.1. previously answered many relevant points around this research question. A robust framework has been developed (see 6.1.2.1.) and evaluated extensively throughout chapter 4 such that it has been shown to provide functional requirements, as intended.

Sections 4.1.5., 4.2.2.8., and 4.3.3. have shown that the framework is very effective in enabling capable solutions to be produced to "meet functional system requirements". 7 actuators are developed in total in this project, whilst the elements of the framework are applied many times more than that. This is achieved by the framework ensuring that the right information is specified to inform the process, then through guiding the process with assistive tools to "facilitate" the right components being selected to deliver on the "functional system requirements". In that respect, with reference in particular to case study 2, the framework is very effective from a methodology point of view; the general and specific guidance of the process are corroborated almost universally by existing literature (section 5.2.). In terms of its effectiveness in producing solutions, it is very effective as shown by testing, and as discussed throughout the thesis it is found to be logical and intuitive, enabling quick interpretation of information.

Iterative and repetitive exposure of the framework to a series of challenges has enabled conclusions to be drawn regarding the efficacy of the framework. Its effectiveness can also be discussed in terms of its versatility; it has been exposed to volume and variation in design of different systems. With no major inhibitors to its use in those applications encountered, and the framework is observed to function well and be appropriate in use; i.e. the framework has not had to be "forced" to work, and any issues which have been encountered have been discussed openly, as per joint 1 of case study 1.

The simple answer to the question posed is that the framework proposed is effective in producing solutions to meet "functional system requirements", as evidenced throughout case studies undertaken. The framework developed has shown capability to produce results better than those reached by an instance of a typical *ad hoc* method, and the framework has produced a range of other solutions which meet the design requirement and do so whilst meeting other requirements determined during application. Across the entirety of the chapter5 and 6, detailed breakdown of specific elements of application which support this averment have been provided. In particular, sections 5.3.2. outlines the completion of objectives aimed at allowing the answer provided to be contrived. Completion of objectives further supports assertion that the question has been answered.

6.3. Review of the Research Hypotheses

Two hypotheses have been introduced in section 1.4. The extent to which they have been confirmed or refuted are discussed in the following sections.

6.3.1. Hypothesis 1

> *A systematic process to guide component selection tasks can be implemented which supports selection of key components required to enable solutions to meet their pre-defined requirements*.

This hypothesis can be broken into two parts:

- Implement a systematic process to guide component selection tasks; and
- Enable selection of components to meet pre-defined requirements.

As has been dealt with throughout chapter 3, a solution has been developed in the form of a framework. The framework is systematic, and evidences a logical step-wise flow, leveraging unique and novel methods to support each step. It has been dealt with in section 5.1. how various aspects of the framework proposed have been refined throughout this study ensuring that the framework has been developed and then exposed to a range of activities of the type it would be expected to support. This has facilitated attainment of the second part.

Through assessment in a diverse range of applications, the framework has been shown to support systematically approaching selection tasks from early design requirements through to specification of individual component instances. Guidelines, and the framework have been shown to provide the necessary decision-making support to enable this task to be supported logically and in a step-wise manner. As the systems have demonstrated their ability to attain the pre-defined performance, it is considered that the solution proposed is capable of facilitating selection of components to meet requirements of a design task.

6.3.2. Hypothesis 2

> *It will be possible to utilise graphical methods to represent component performance information in a format which is suitable for interrogation to make component selection choices.*

Literature review elucidated a handful of instances where selection of engineering entities had been explored by means of using graphs, with the most successful instance in materials selection (Ashby, 2005). Exploration in this thesis has examined whether they are able to support throughout the process of component selection from concept level to specification of a specific component model. Use of graphs has also been expanded to consider a range of components never previously before noted to have been covered in this way. This has shown that it is possible to represent component performance in this way, with issues encountered documented earlier in this report.

As system requirements have been able to be met, the graphs can be considered to have supported interrogation and then selection choices, since only this method has been used. This has allowed demonstration that the graphs produced are a viable solution for assessment of component performance information and that they are able to facilitate interrogation for selection to take place.

6.4. Summary of Contributions

The research presented is considered to contribute a range of new and interesting insights, with varying significance. Some of the major contributions are outlined broadly as follows:

1. Several areas of knowledge where there is a need for contribution have been outlined, concisely summarised by figure 35 in section 2.6.1. From this summary, clear definition of requirements of a solution to component selection have been elucidated, as per table 4 in section 2.6.2. These efforts have clarified existing shortcomings and knowledge gaps for which solution development is worthwhile and justifiable;
2. A framework has been developed, targeted at resolving perceived lack of formal component selection strategies for mechatronic actuators. In particular, this focused on deploying this in

conjunction with newly developed tools, exploration of which also interested the researcher, having utilised similar tools in other engineering tasks. In support of the framework for approaching component selection, guidelines have been developed, whilst supporting tools in the form of graphical component performance charts, and qualitative reference databases have been developed - all of which are unique to this work, as are the lessons learnt from their implementation;

3. Idiosyncratic supporting knowledge necessary to effectively apply the framework has been developed and tested. A theoretical understanding of the utility of performance indices, as well as developing equations governing their effective use has subsequently been put forward and tested, amongst various other aspects of the solution developed;
4. Utilisation of other sub-elements of this work, such as AHP to provide precedence to criteria ranking are also novel and noteworthy. These have been tested and proved out. This has been shown to have benefitted the selection process by adding rigour to the manner in which choices are made surrounding the significance of criteria based on requirements;
5. By means of categorising actuation components and developing hierarchical structured taxonomies of these, and extending this to higher levels. Definition and taxonomy of components used in actuators has been clarified in a way not noted in literature previously;
6. Through 3 in-depth case studies, which have seen the system applied to development of 7 separate actuators of varying complexity and utility, the framework has been shown to support delivery of solutions to meet system requirements, and the exact manners in which it is effective and has potential for further development have been highlighted. The system has been utilised in development of systems and shown promise in a range of ways;
7. Understanding of how the framework operates not just in terms of outputting solutions, but also how it fits within system design strategies has also been created and presented, as per section 4.2.3. This has helped clarify *where* this framework should be relied upon in design tasks. Information pursuant to how this approach compares to other design tools is also suggested, as per figure 102; and,
8. Provision of informed and clearly identified requirements to push this research work on to new, more effective levels of application. This has laid a clear path for future development of this work which was previously not specified, and which is summarised in section 8.5.

6.4.1. Significance and Impact of Overall Contribution

In section 2.6., it has been stated that "*succinctly, this work seeks to establish a new component selection solution, which brings greater rigour and robustness to the process*". The rationale for making this statement has been that, from review, it is noted that no existing formal processes supporting component selection are found. It is also known from interviewee response (section 4.1.6.4.) and reference from key literature (Vogwell & Culley, 1991) (Harmer et al., 1998) (Poole & Booker, 2011) that component selection is a process often completed in an ad hoc fashion, where instinct is followed rather than any formalised methodology, method, or framework.

In response, the overall framework structure has prescribed a step-based system of supporting not only the process flow for decision-making, but also novel and effective methods which can be leveraged to support the process of selection and the order in which they should be consulted. Step-wise guidelines support the process of selection in terms of drawing attention to key information, as well as supporting decision making at key milestones. Graphical communication of information has also proven to be a powerful tool in conveyance of relevant information to aid selection. Distinctly, each of these sub-elements provide a useful means to address selection processes; however, in tandem the form a potentially extremely potent solution to aid engineers in selection tasks.

6.4.2. Impact of Contributions and Application in Future Design Practice

Fundamentally, the proposed work has been undertaken as a means to inform and improve future design practice. In doing so, several stakeholders are likely to be affected in differing ways. It is worth delineating the manners in which they might expect to be affected. Broadly, those affected by the development of the proposed approach can be considered as engineering designers (specifically, those undertaking specification and acquisition of components when designing some system), future research practitioners, and suppliers and original equipment manufacturers

6.4.2.1. Engineering Designers

The proposed framework and its supporting tools have been developed with engineering designers in mind. Information sought and documented from literature review has largely been related to issues engineering designers encountered in selection tasks, and the subsequent design specification of section 2.6.2. sought to address issues to enable easier and more effective task completion for practitioners.

Subject to further development, it is considered that engineering practitioners would be the primary beneficiaries of this. The manner in which they are proposed to benefit is much as described throughout this thesis. It has already been covered in 6.4.1. how a more rigorous and methodical approach to component selection has been instantiated as an outcome of this work. It would therefore be expected that engineers would be able to reference and rely upon a central framework governing the key tools and processes to be adopted in selection of components, whilst they would be guided by step-wise guidance with many steps supported by tools tailored towards aiding *effective* completion of this specific task.

As documented from literature review and assessment of other commercial solutions, it has been observed that component selection is acknowledged as a key task in system design; however, no formal methods of the type proposed are considered to be in existence, whilst no methods like those proposed are encountered either. The framework and methods proposed are based on rationale developed from literature and commercial review, which pointed to the need to develop tools to aid selection and to guide the overall process. Engineers are the party most likely to interact with this solution, so are a significant party in terms of expected users.

6.4.2.2. Future Research Practitioners

It has been covered in section 5.5. how there are a range of potential future research tasks which would strengthen the knowledge and understanding surrounding the proposed framework. These suggested further works are of relevance to future research practitioners who may wish to explore these recommended avenues further as a means to enhance knowledge of this subject matter.

In addition, subject to the framework and its methods being developed further, research practitioners may have use of this approach for implementation in projects where the framework is not the focus, but a tool relied upon. Examples of this include research instances where engineers' behaviours in design tasks are being examined, studies requiring development of a new system where the framework is used to do so, or other similar uses.

6.4.2.3. Component Suppliers and Original Equipment Manufacturers

The final key stakeholder identified as a beneficiary of the framework proposed are OEMs and suppliers of components of the type covered in this project. These two stakeholders are considered to be affected by the framework in a way which is different to that of those examined in 6.4.2.1. and 6.4.2.2. Suppliers and OEMs are likely to be affected by how their *customers* interact with the selection process (researchers and engineers using the framework may affect the suppliers and manufacturers), but component suppliers and OEMs are also in a unique position in that they are positioned to leverage the solution to *convey* information rather than just *interrogate* the information. That is, researchers and engineers will primarily be concerned with review of information which is created *by* OEMs and suppliers. Both types of stakeholder are affected by the same relationship, though in different ways.

As suppliers and OEMs are required to produce tailored graphs, databases, and guidelines it is useful to provide an overview of how these stakeholders are advised to approach this task. This is provided as follows.

6.4.3. Recommendations for Implementation in Software

As alluded to in section 5.5.1., it is recommended that this work should next be embodied in a software platform. As a means to guide this task, some specifications regarding the performance of that solution are provided, as per table 39. This is provided as high-level points which capture the functionality a software solution should have.

Table 39: Proposed specifications that recommended software solution should have.

<table>
<tr><td>Scott Brady
Ph.D. Thesis</td><td>Recommended specifications of software embodiment of component selection solution</td><td>24/08/2020</td></tr>
<tr><td colspan="3">Requirements</td></tr>
<tr><td colspan="3">General Requirements:
- Software should operate with a graphical user interface with similar layout and functionality to comparable software design aids: Solidworks, ANSYS, Granta Selector, etc.
- Layout should facilitate straightforward transition between tools used in proposed selection process.
- Should facilitate addition of new component types, additional criteria, etc.
- Should be kept up to date with changing information (cost, availability, etc).
- Examination of information at varying levels should be facilitated; i.e. examination of high-level information about “electric motors” should be provided, as well as detailed information on “shunt wound brushless DC motors”, for example.</td></tr>
<tr><td colspan="3">Support interactive use of graphs:
- Support automated graph generation from database information so that custom graphs can be made two compare criteria of interest.
- Should support zoom functions such that comparison is more easily supported in instances such as that discussed in figure 105.
- Support interrogation of component classes, sub-classes, and individual instances.
- Enquiry of individual component instances should provide scope to review all information relevant to that instance; data sheet, cost, availability, etc.
- When reviewing component families, classes, and sub-classes, it should be possible to review qualitative databases associated with the quantitative graph-based information.</td></tr>
<tr><td colspan="3">Support use of qualitative databases:
- Qualitative databases should be available for review in a standardised format.
- Qualitative databases should be accessible through the hierarchical taxonomies proposed, but also through the graphical interfaces. This supports easy reference of both qualitative and quantitative information.</td></tr>
<tr><td colspan="3">Support decision-making:
- Embed developed guidelines as a template which guides the process in steps; i.e. page 1 prompts input for requirements, step 2 prompts conversion into actuation specifications, and so on.
- Steps where calculations, etc. are required should be supported as proposed in Oriental Motor’s solution, discussed in figure 19.
- User should be supported through development of pair-wise comparison process, with software automatically producing order of precedence based on user inputs to pair-wise comparisons. Omit need for calculation by user.</td></tr>
<tr><td colspan="3">Support selection with respect to other components:
- As well as supporting this through guidelines, an eventual solution should seek to explore use of automated component suggestion like that used in Beckhoff Automation’s solution, discussed in figure 104.</td></tr>
</table>

6.5. Concluding Remarks

Throughout this thesis, the researcher has attempted to breakdown and make clear the key learnings and developments from each chapter. This has been summarised throughout, but particularly in chapters 5 and 6. Much detail has been provided as to the developments which have taken place throughout each chapter, and, latterly, has went into detail regarding the extent to which the project aim and research question have been answered (6.1. and 6.2.), and the accuracy of the hypotheses posed at the outset (6.3.). The extent to which supporting objectives and other desirable outcomes of this work have been achieved have also been discussed throughout 5.1. and 5.3. The limitations (5.4.) and routes to further development of this framework (5.5.) have also been clarified.

The project has aimed to be thorough in all senses. Literature review covered all depths of the subject matter, expanding beyond typical review of academic publication to consider commercial solution, etc. Research design also explored all options available to the researcher to assess this framework. Variety and intensity of challenges to which the framework have been exposed, and the assessment and reporting of data have all been conducted with as much depth as has been possible within the project's constraints. It is considered that this has resulted in a robust answer being provided to the question that this research has asked, and an overall good solution being provided.

Notwithstanding this, the research study is acknowledged to have some issues (5.4.1.), whilst the solution also has issues (5.4.2.). Whilst it would clearly be preferable that issues were not encountered and that the approach already had the capability detailed in section 8.5., it should also be acknowledged that these sections themselves contribute to knowledge; they allow a clear cognition of the next problems presented, and suggestions on how they should best be approached.

The research venture has provided a new, valid, and effective solution for component selection in robotic system design, but one which requires further development to industrialise. This first step in developing this type of framework has built a strong foundation, facilitating further development towards higher readiness-level than at the project's outset. The theory of the proposed solution has shown great promise, and with further development could represent a paradigmatic shift in the way that some component types are selected, and can be a tool to complement existing approaches.

It has previously been commented in this thesis that "the problem, it is argued, is that in addition to comprehensive databases and methods for database interrogation, there exists no effective "systematic sequence of thinking operations" for component selection for the use case in mind". The solution proposed in this work has shown great promise in providing a solution which would supply this systematic sequence of operations, also supported by a novel graphical method.

Glossary of Terms

The following definitions cover the key terms used in this thesis and the meaning attributed to them as they have been applied throughout this document.

Actuator: A sub-type of component or component arrangement which provides the driving force or torque necessary to elicit the motion and performance necessary to achieve a desired effect in terms of movement of some system or series of systems. Further expanded upon in section 1.5.

Component: This thesis defines a component as some engineering entity with readily available functionality, usually as the result of a manufacturer's operation; e.g. actuators, bearings, batteries, etc. (Cebon & Ashby, 1997)

Component Selection: The decisions and processes undertaken in order to sequentially remove from consideration various prospective solutions until an individual component is able to be chosen. See also: **component**, and **selection**.

Design Method: This work defines a design method as some tool of aid which is leveraged to assist solving "individual design problems or partial tasks" (Page 9, Gerhard Pahl et al., 2006)

Engineering Designer: An engineer of any discipline tasked with the "mental creation" (Gerhard Pahl et al., 2006) and development of a physical system to provide a solution.

Engineering Entity: An engineering instance of a physical item or a process which relates to use in engineering, often noted to contain materials, components, assembled products, or manufacturing processes (Cebon & Ashby, 1997).

Framework: Frameworks have been described in literature as a "blueprint" (Grant & Osanloo, 2014) and a way of "systemising" (Adom & Hussein, 2018) concepts and elements of research. In this work, the framework is defined as the system and structure which defines the relationships and the flow of information between all other aspects of the contributed methods, similar to comparable frameworks (Calvert et al., 2011).

Guidelines: In this work the term "guidelines" is used to describe the systematic process flow associated with step-wise instruction or guidance which is recommended. Similar use of this terminology is also seen in other peer-reviewed literature in mechatronics design (Salem, 2014).

Mechatronics: A system integrating sensors and instrumentation, processing systems, actuation capability, and engineering design (D. A. Bradley et al., 1993). This definition is expanded upon in greater detail in section 1.5.

Mechatronic Design Process: The engineering design process, including all tasks, decisions, and development involved in the ideation, development, and delivery of a mechatronic system.

Selection: An act involving the requirement to make a choice (Cebon & Ashby, 1997) or choices to enable selection of some entity. This thesis is primarily concerned with selecting engineering entities. Selection as a process is expanded upon in greater detail in section 2.2.

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Appendices

Appendix A - Chapter 2

A.1. Further V-Model Examples

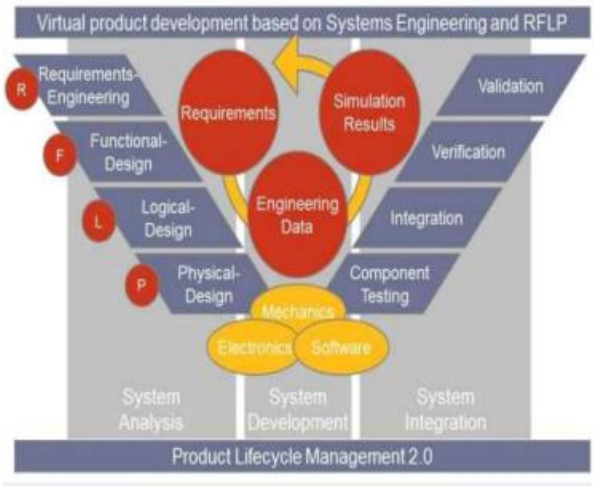


Figure 106: RFLP (Requirements, functional, logical, and physical) Method (Mlambo et al., 2018)

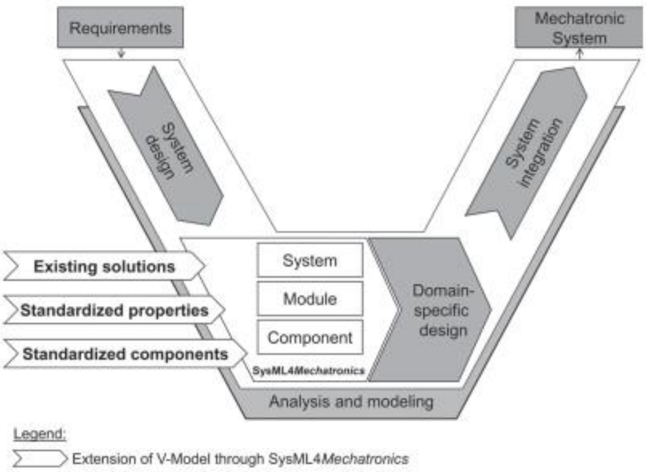


Figure 107: V-Model - Kernschmidt

The process of component selection is acknowledged in existing methodologies, but the significance of *correctly* and *effectively* completing this task is often overlooked or trivialised:

> "This is followed by a detailing of the components up to the determination of the tolerances and fits required for the fulfilment of the function as well as all manufacturing regulations. Mechanical components include housings, covers and flanges of control units in addition to those used to transmit forces or moments. For electrical and electronic components, for example, associated printed circuit boards are designed and the electronic components

selected, Application-Specific Integrated Circuits (ASICs) specified or reconfigurable circuits (field programmable gate arrays, FPGAs) selected as prefabricated components." (Page 319, Iris Graessler & Hentze, 2020)

Specific mention is also made with regards selection of actuation components:

> "In addition to the circuits, sensors and actuators are developed or selected and the electrical infrastructure is designed." (Page 320, Iris Graessler & Hentze, 2020)

In addition to the V-models specifically discussed, a range of others have also been consulted (Peter Hehenberger, 2015) (Kernschmidt et al., 2018). It has been found that similar level of allusion to component selection is found and that a comparable absence of guidance to support the activity is also found. Whilst the significance of the task is acknowledged as key in design processes, mechatronic design approaches tend to assume that selection will be made effectively and without error.

A.2. Selection Guidelines

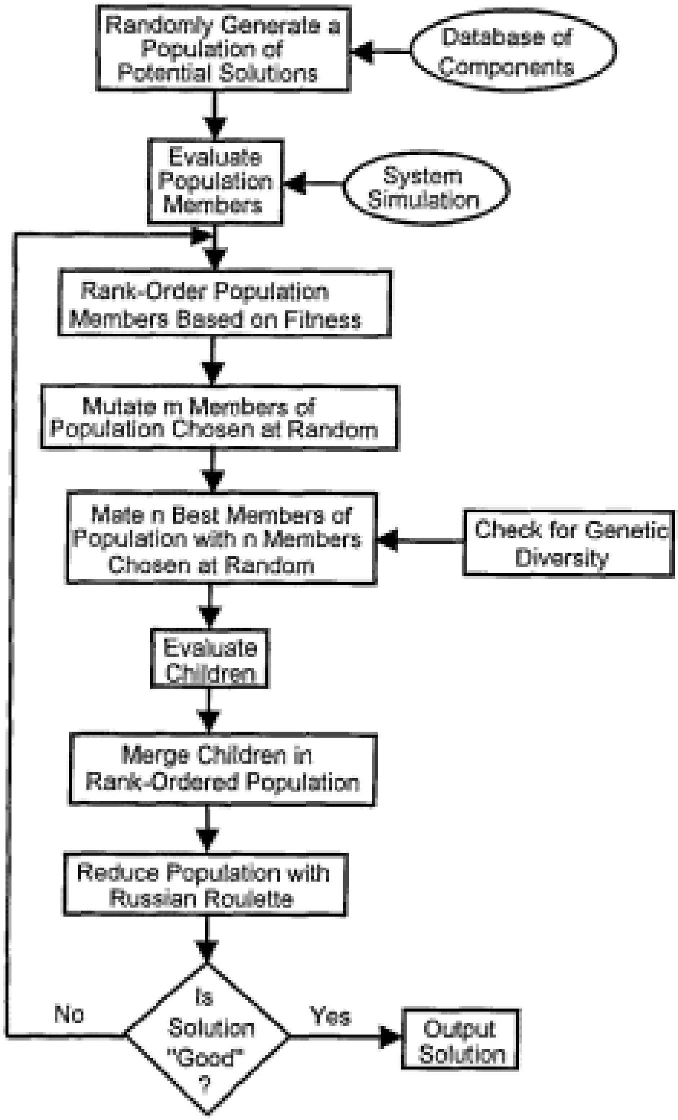


Figure 108: Carlson (1996)

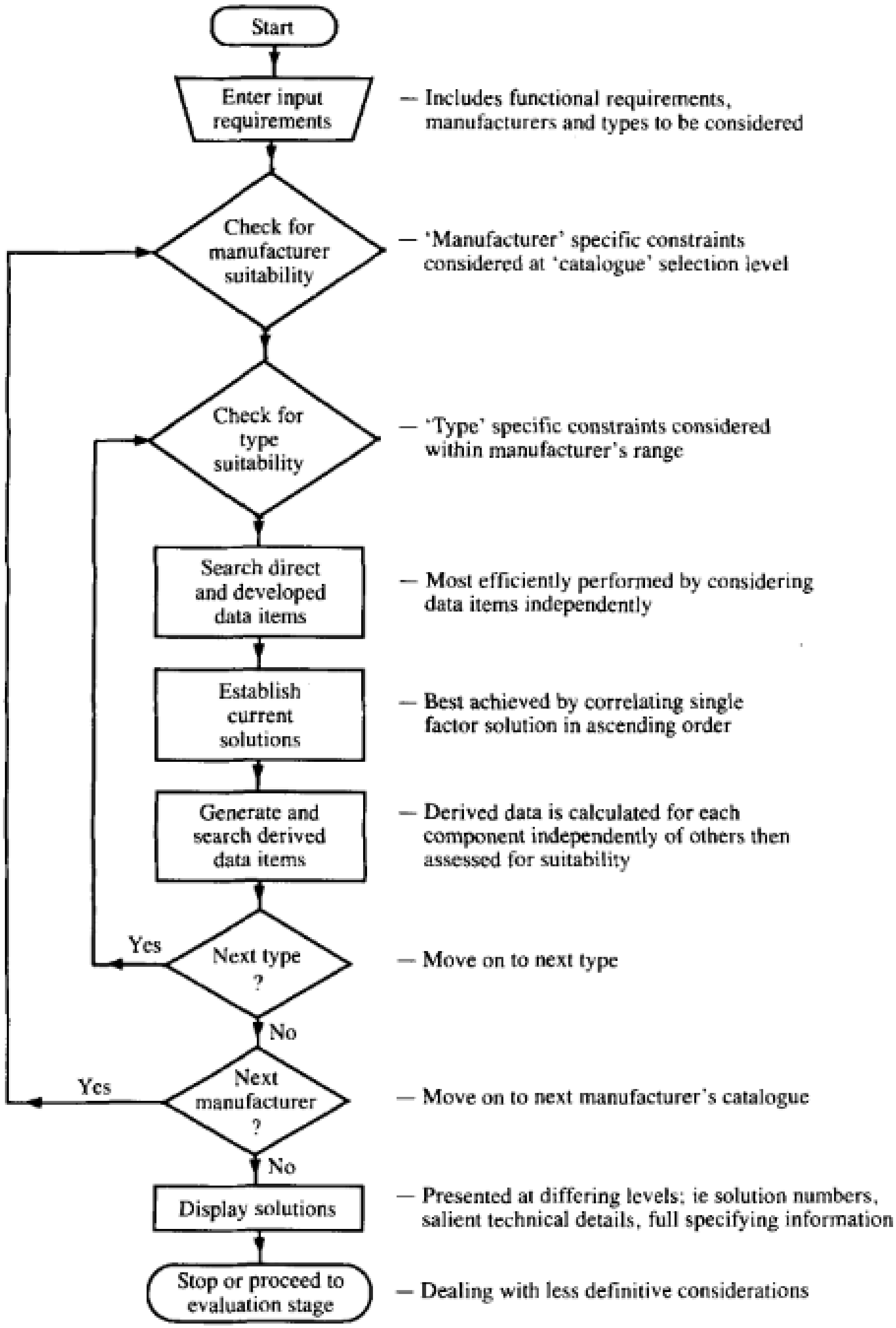


Figure 109: Vogwell (1991)

A.3. Additional Graphs Examples from Existing Application in Engineering

Beyond the quite specific instances covered in previous sections to communicate specific types of information, graphical methods of conveying information are seen ubiquitously throughout engineering. Simulation software packages such as ANSYS, Adams MBD, Virtual Robotic Experimentation Platform (V-REP), Abaqus, etc. rely heavily on graphs to communicate performance expected through simulated results. This is illustrated in figure 110. Communication in this way is also shown to be extremely effective in relaying information to those interested in interrogating such information.

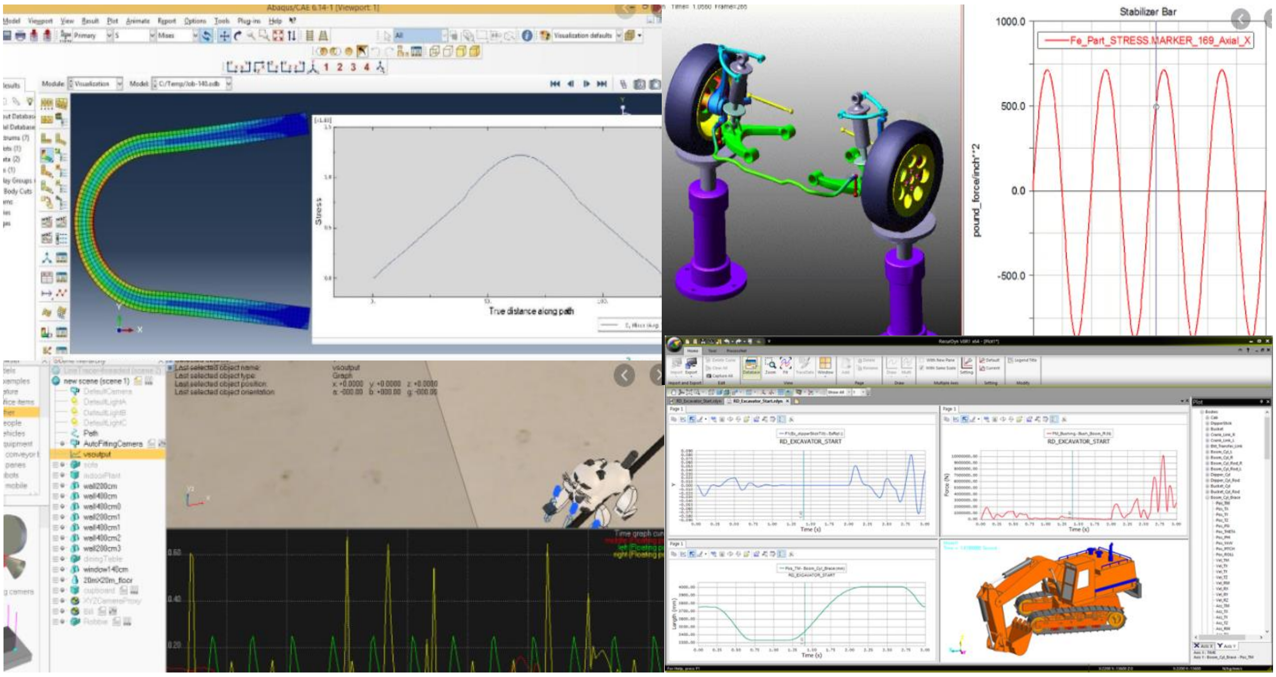


Figure 110: Simulation software heavily relies on graphical communication of engineering information. Clockwise from top left: Abaqus; Adams MBD; ANSYS; and V-REP.

Graphical methods of communicating information in engineering are also noted to exist to operate at higher levels of granularity. Most instances covered in review so far communicate information on specific performance of a system’s performance or of expected performance from a specific entity of component. Graphical methods have also been shown to be used to highlight the types of design tools used in engineering (Peter Hehenberger, 2012), helping readers to understand where there is still a need to develop new technologies to assist engineers in new ways. This is depicted in figure 111.

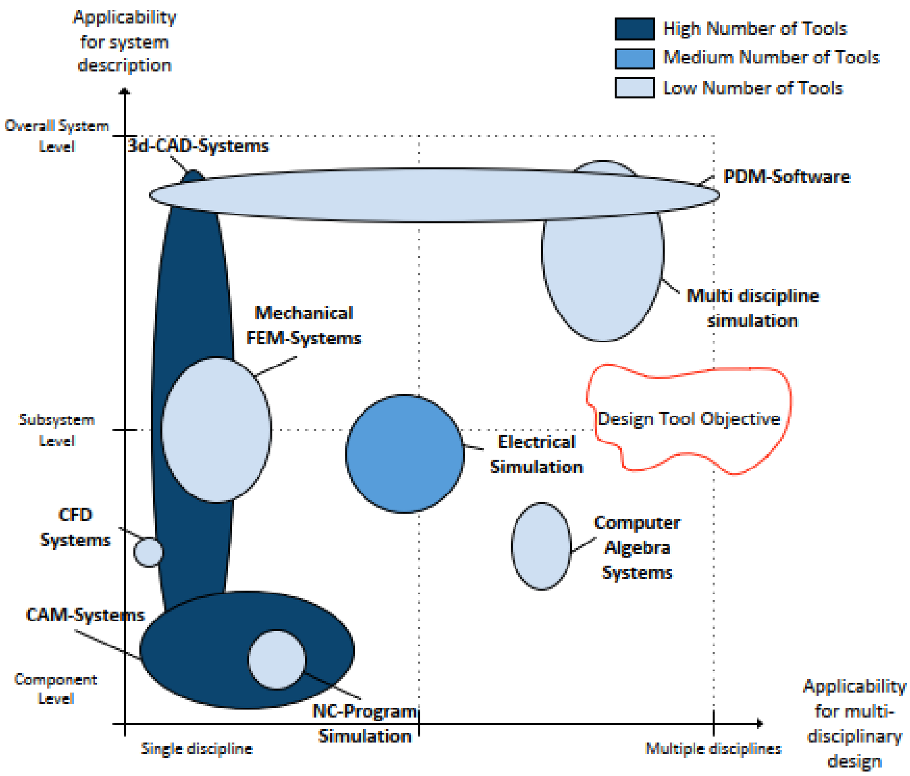


Figure 111: Graphical approach has previously been used to represent the tools utilised in mechatronic design (Peter Hehenberger, 2012).

Other uses of graphs include those such as Weibull-based estimation parameters, which is observed to be utilised to demonstrate distributions and changes. Review has shown several examples of this used in an engineering context for estimation of material performance (Nohut, 2020) (Lei et al., 2020) (Pérot & Bousquet, 2017). The broad range of applications of graphs for presenting information clearly demonstrate the effectiveness and graphs to convey information. It is, therefore, reasonable to suggest that as a means to convey information to assist component selection this is an avenue worthy of further investigation.

A.4. Enlarged Literature Review Summary

1st author	Year	Taxonomy and classification of components	Graph use	Guidelines, methodology, or systematic sequence of operations	Formalised approach to decision-making (MCDM, etc.)	Assisting assessment or conveyance of qualitative information	Supporting selection with respect to other components in the actuator system	Use in Actuator Design
Huber	1997	O	X					X
Harmer	1998	O	X	X				
Vogwell	1989	O		O		X		O
Cebon	1997	X	O	X		O	O	
Vogwell	1991			X			X	O
Poole	2011	X	X	X				X
Carlson	1995			O	O		X	O
Ashby	2007	O	X		X			
Cuttino	2000		X	X	O		O	X
Zupan	2002	X	X					X
Kok Sim	1991	X		X		O		
Hicks	2002	O	O	X			X	X
Egbuna	2009	O		O	O	O		O
Akhtaruzzaman	2011			O				X
Begey	2020			O				O
Culley	1992	O		X		O		O
Madden	2005							X
Cheng	1995	X		O		X		

Appendix B - Chapter 3

B.1. Components to be considered

B.1.1. The Sample Database

To represent component performance graphically it has been necessary to tabulate information. It is neither feasible nor practical to collate all information on **every component available**, therefore a sample database has been used to create this *generalised* overview, and has sampled the most important criteria of the most relevant components.

Considered Components

It has obviously not been possible to cover every component type and collate every conceivable component graph. As such, the most pertinent components have been covered as far as possible; those typically used in robotic actuators, as per figure 112, below. The focus is on components which enable physical performance of the system; motors, transmissions, brakes, sensors, and bearings; i.e. motor controllers, power supplies, etc. are omitted at this stage.

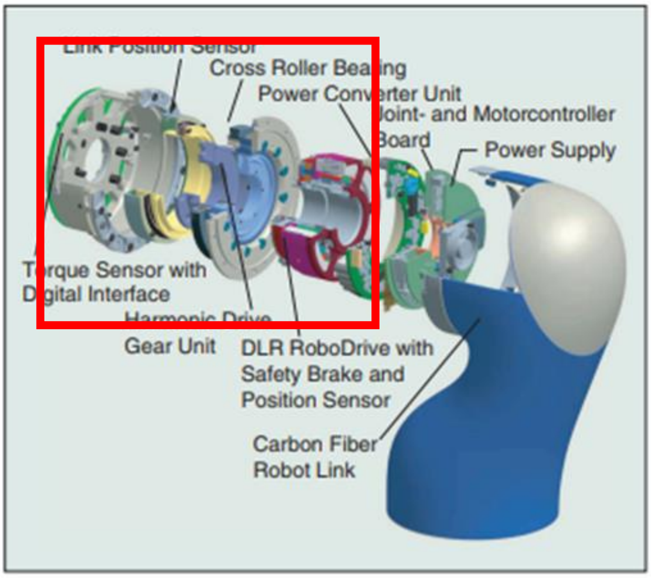


Figure 112: Breakdown of critical components typically found in robot joint actuators. Red boxed region highlights key components considered in this thesis. Image: (Albu-Schaffer et al., 2008)

In addition to leaning on information from literature, the researcher's professional role as robotic and automation technical lead at a research centre and the experience that has brought in hardware development has allowed some input based on experience.

B.1.2. Criteria to be covered by the framework

Criteria for representation

This section outlines the most relevant information considered during graph compilation. Other criteria will still be relied upon during the study, but it is impractical to convey *all* quantitative data in graphical form at this stage.

In this project, the criteria used will not be exhaustive. This work seeks to ascertain whether this approach is effective and valid, therefore representation of crucial criteria is sufficient to make necessary assessments. Exhaustive criteria representation would result in thousands of graphs being developed. This is not necessary to make the assessments required by this thesis. Criteria believed to be the most influential criteria for each component type have been selected; since they are crucial criteria they facilitate proof of concept of this approach.

Definition of key criteria

In identifying the key criteria on which to compare components, 4 key points are considered:

- Current and future robot system requirements;
- Inputs from expert and peer-reviewed sources;
- Information frequently portrayed and relied upon in component datasheets; and,
- The researcher's own experience and understanding.

Additionally, criteria to be considered must allow the engineer to select components to meet system requirements.

Graphical representation of engineering content in this work has unique challenges. When representing components various issues are encountered: changing criteria sets for different component types, for example. As such, the criteria for assessment must change with each component type. Additionally, sometimes the *same* component types have different criteria; stepper motors have step angles, whilst other motors do not. This increases difficulty of the compilation process and necessitates alternative approaches to represent this information, but is necessary to accurately convey quantitative information on components such that this framework is usable. A proposed solution to this is to plot an "alternate" X or Y axis and use this as the reference for alternate information.

Having identified the complexity of conveying specific criteria, it would make sense to deal with unchanging criteria common to all (or most) component types first.

Criteria affecting all components

Significance of mass reduction (Albu-Schäffer et al., 2007) (Dorsey, 2015) (McMaster & Yan, 2016) (Lessard et al., 2016) (Post, 2016) and energy efficiency (Chemnitz & Schreck, 2011) (Uhlmann et al., 2016) (Verstraten et al., 2016) (Pellicciari et al., 2013) (Bhatia, 2014) are clearly necessary, whilst the inclusion of cost reduction is somewhat axiomatic.

These considerations scratch the surface of interest in mass reduction, energy efficiency, and cost reduction throughout engineering design processes. It is on this basis that it is considered necessary to represent the following criteria for all components wherever necessary:

- Mass;
- Energy consumption; and,
- Cost in terms of monetary purchase price.

The crucial nature of these criteria mean that they will be considered across the board, where applicable.

Criteria specific to each component type

In this chapter's appendices, a blow-by-blow account of how component criteria has been refined is presented. This process went through iteration across a range of criteria, justifying step-by-step the reasons why criteria were sequentially omitted. The rationale for omission of criteria was based in large part on qualitative discussion with reference to information typically conveyed on component datasheets for the component types under consideration.

In certain cases, there may be requirements to consider other information; e.g. for stepper motors consideration of the range of step sizes must be contemplated, etc. This will be approached on a case-by-case basis.

Source of Data for Criteria

Pursuant to compilation of the sample database discussed already, the **source** of that information is important. Initially, attempts were made to use single manufacturers to ensure consistency; however, there were several issues with this:

1. The range of values generated was not considered to be diverse enough to be considered a "generalisation" fit for proof of concept;
2. Manufacturers not producing certain *key* component types, meaning that other manufacturers had to be sampled (i.e. one motor company not producing DC servos, so another company had to be sampled for this information). Again, unsure this was generalised enough; and,

3. Difficulty in ascertaining certain information from key manufacturers due to poor quality or incomplete datasheets provided with components and poor interfaces for component search on their webpages.

As a means to overcome issues, RS components has been utilised as the core sample source for components *as far as possible*, with other sources referenced where required as a means to add greater depth to the sampled dataset. Owing to the already general sample gleaned from RS Components these additional components are considered to be *part of* that generalisation, rather than biasing it; i.e. they add to it value, they do not take away value. RS Components has been selected as it is a ready-made database of component information. RS Components are the largest supplier of COTS engineering components in the UK, providing a range of components from a range of OEMs. Its use mitigated the following issues:

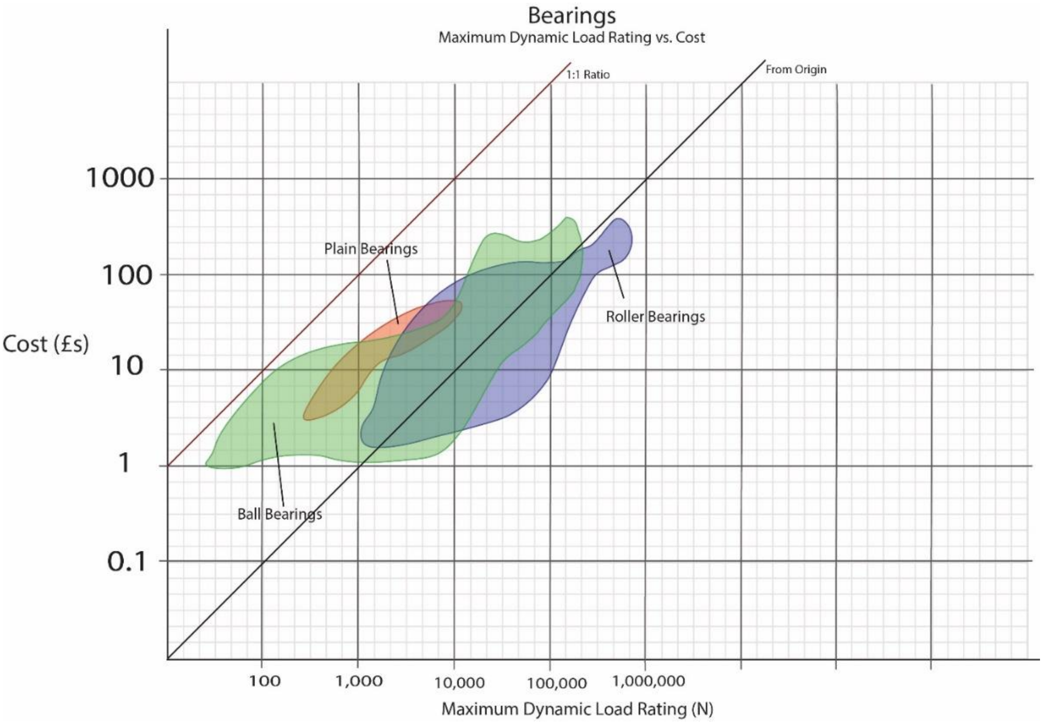
1. It is generalizable as it is a cross-section of the COTS components;
2. It contains better diversity of components than any other known database/platform available in the UK; and,
3. Component information and datasheets are provided for all components sold - though there are still issues with inconsistencies in datasheets, etc.

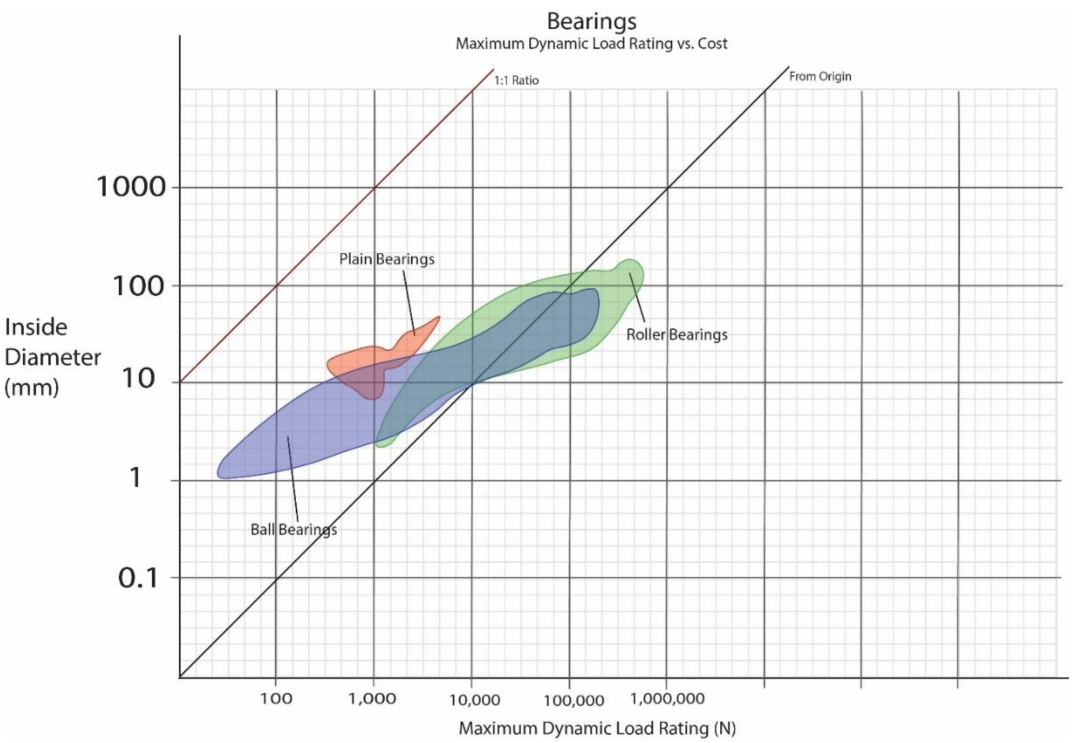
A single source for components with datasheets provided in a single standardised format with a user friendly interface would have been the ideal source; however, since this was not available the researcher attempted to contrive the next best thing from the resources available. Ironically, **this issue** encountered as part of the development of the framework to assist component selection is an issue that the framework seeks to **resolve**, further elucidating the case for this work's undertaking.

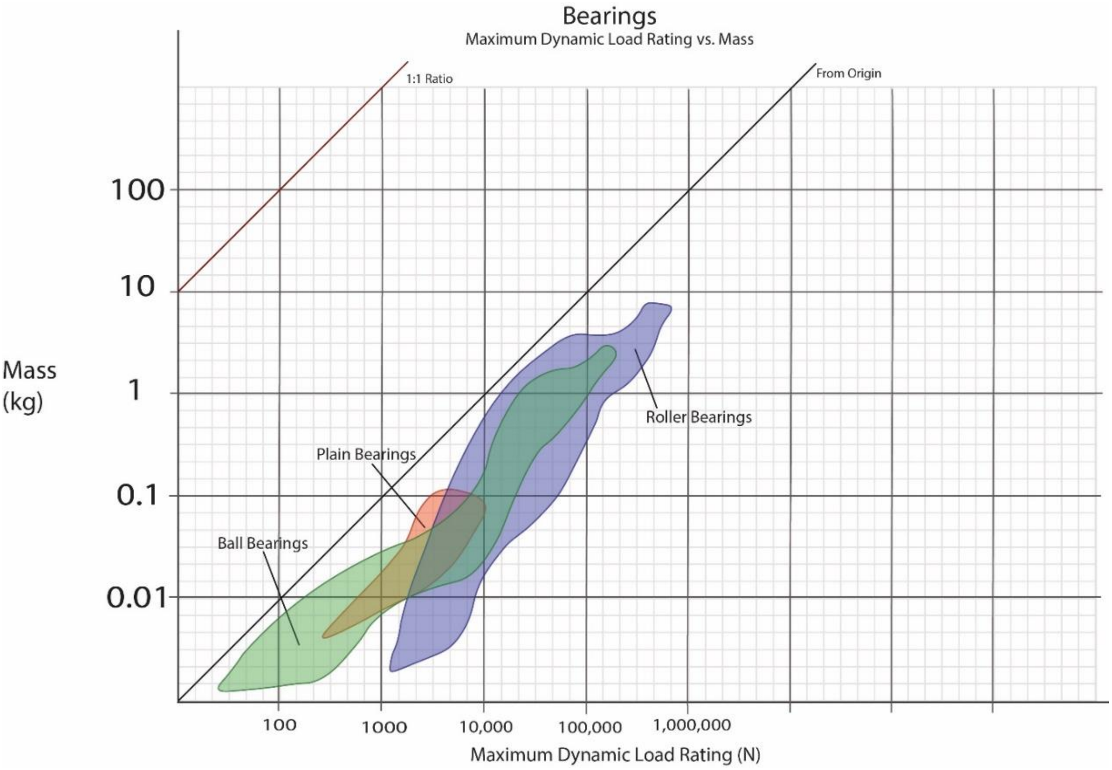
Use of graphs for representation seeks to allow the information to be represented in a manner which permits straightforward intuition and comparison of the information, whilst also highlighting other solutions available. The following sections will discuss the rationale behind the development of the graphs before putting forward examples and some associated discussion.

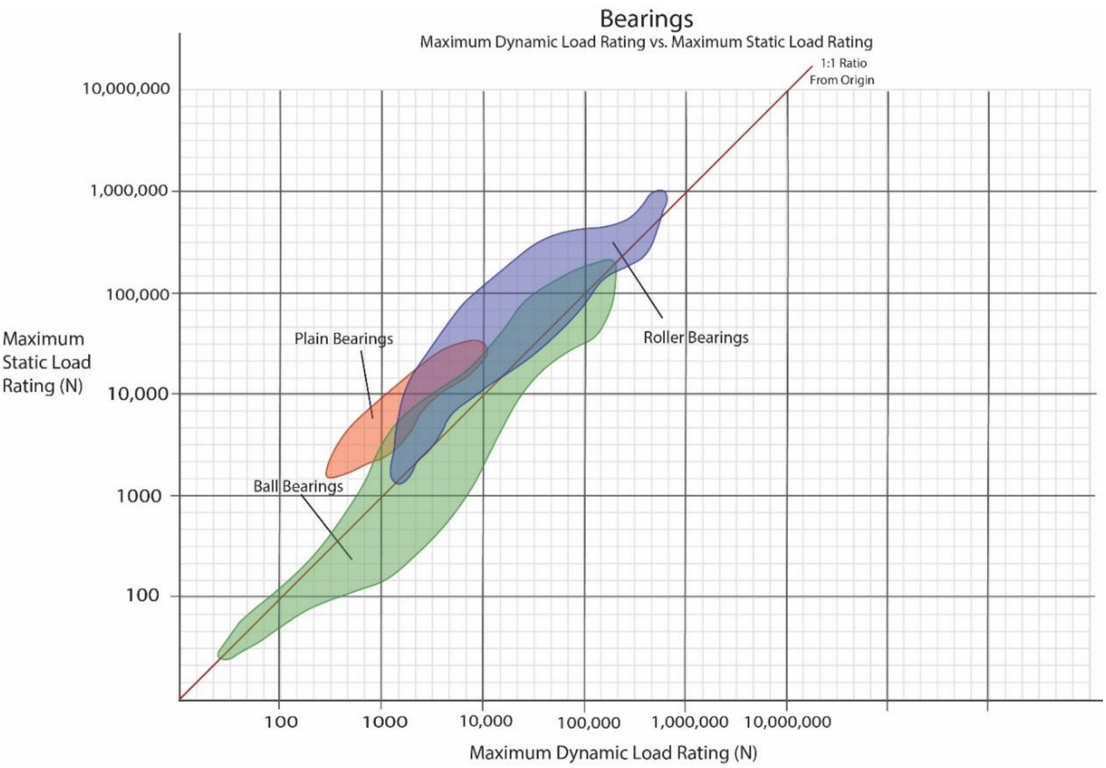
B.2. Provision of all Graphs Generated

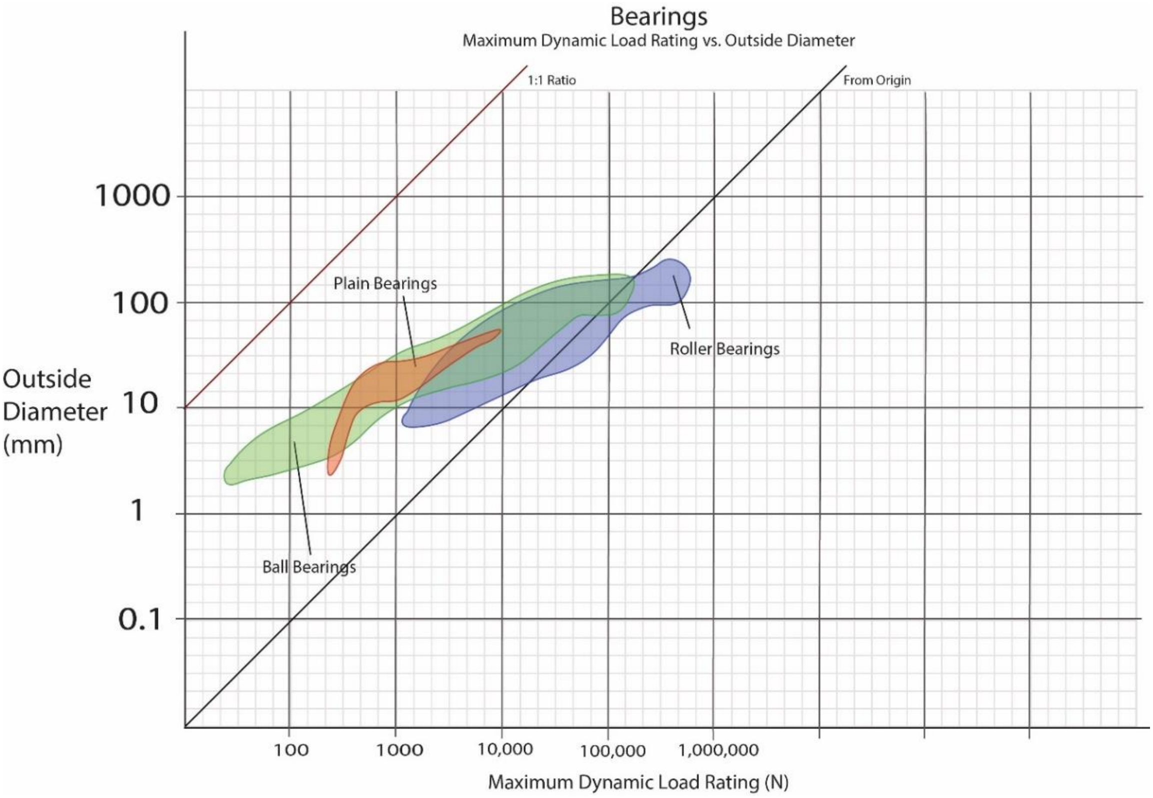
B.2.1. Bearings



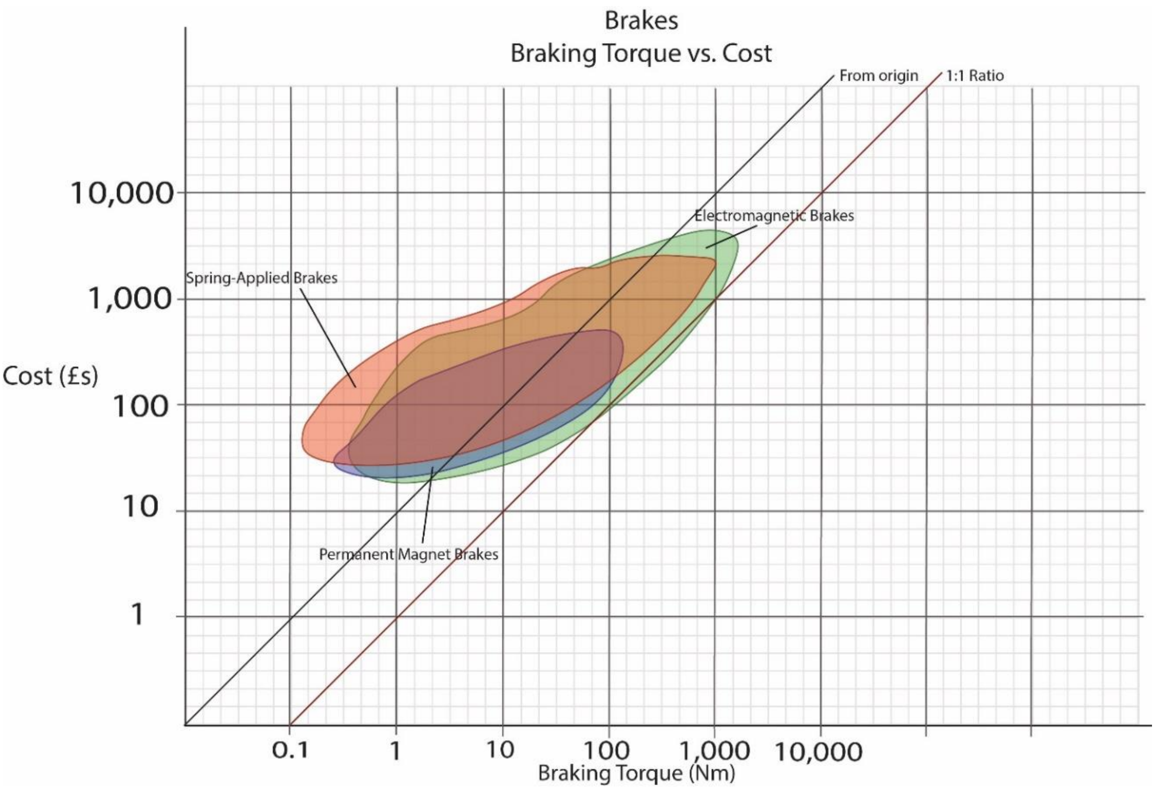


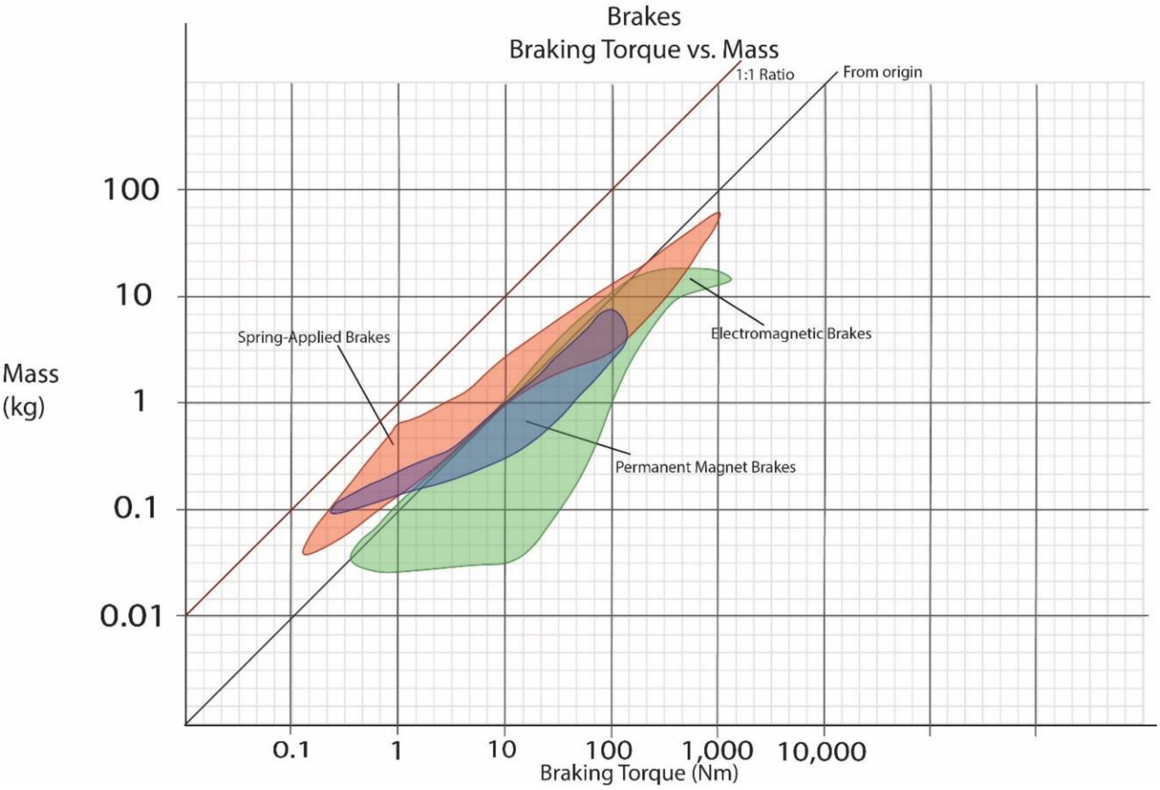

Bearings
Maximum Dynamic Load Rating vs. Mass
1:1 Ratio
From Origin
Mass (kg)
100
10
1
0.1
0.01
Plain Bearings
Ball Bearings
Roller Bearings
100
1000
10,000
100,000
1,000,000
Maximum Dynamic Load Rating (N)

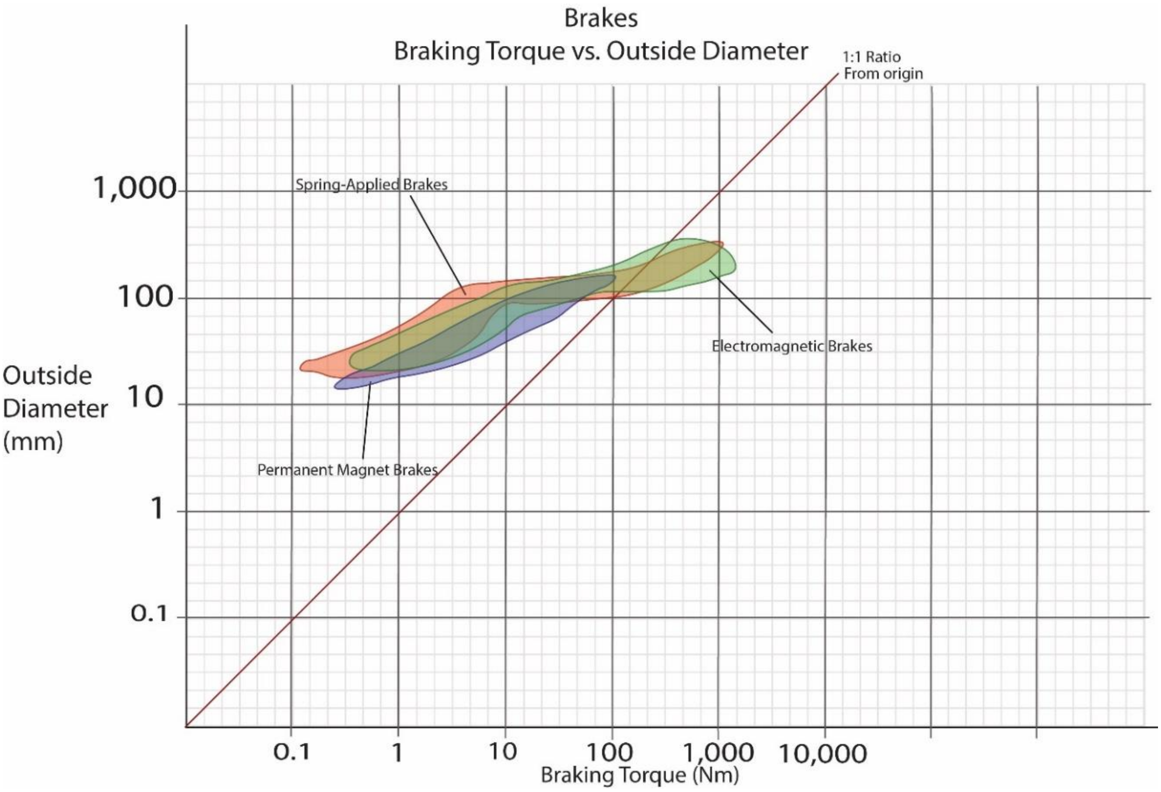

Bearings
Maximum Dynamic Load Rating vs. Maximum Static Load Rating
1:1 Ratio
From Origin
10,000,000
1,000,000
100,000
10,000
1000
100
Maximum Static Load Rating (N)
Plain Bearings
Ball Bearings
Roller Bearings
100
1000
10,000
100,000
1,000,000
10,000,000
Maximum Dynamic Load Rating (N)

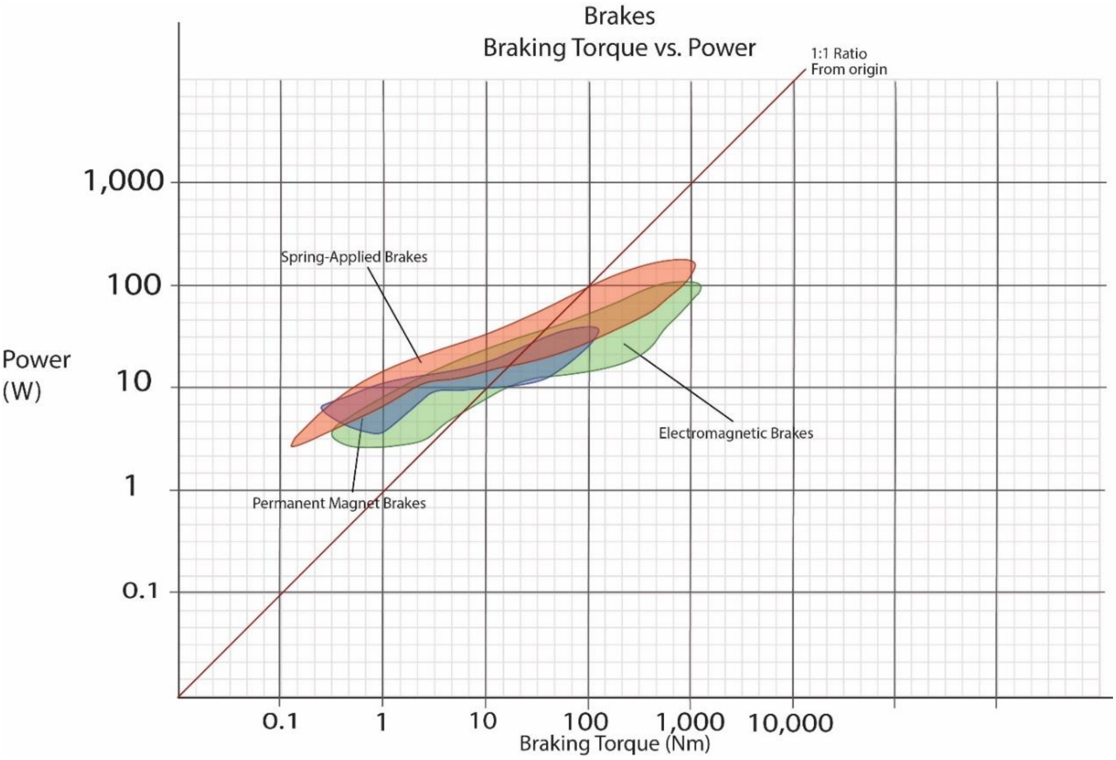

Bearings
Maximum Dynamic Load Rating vs. Outside Diameter
1:1 Ratio
From Origin
1000
100
Outside Diameter (mm)
10
1
0.1
Plain Bearings
Roller Bearings
Ball Bearings
100
1000
10,000
100,000
1,000,000
Maximum Dynamic Load Rating (N)

B.2.2. Brakes

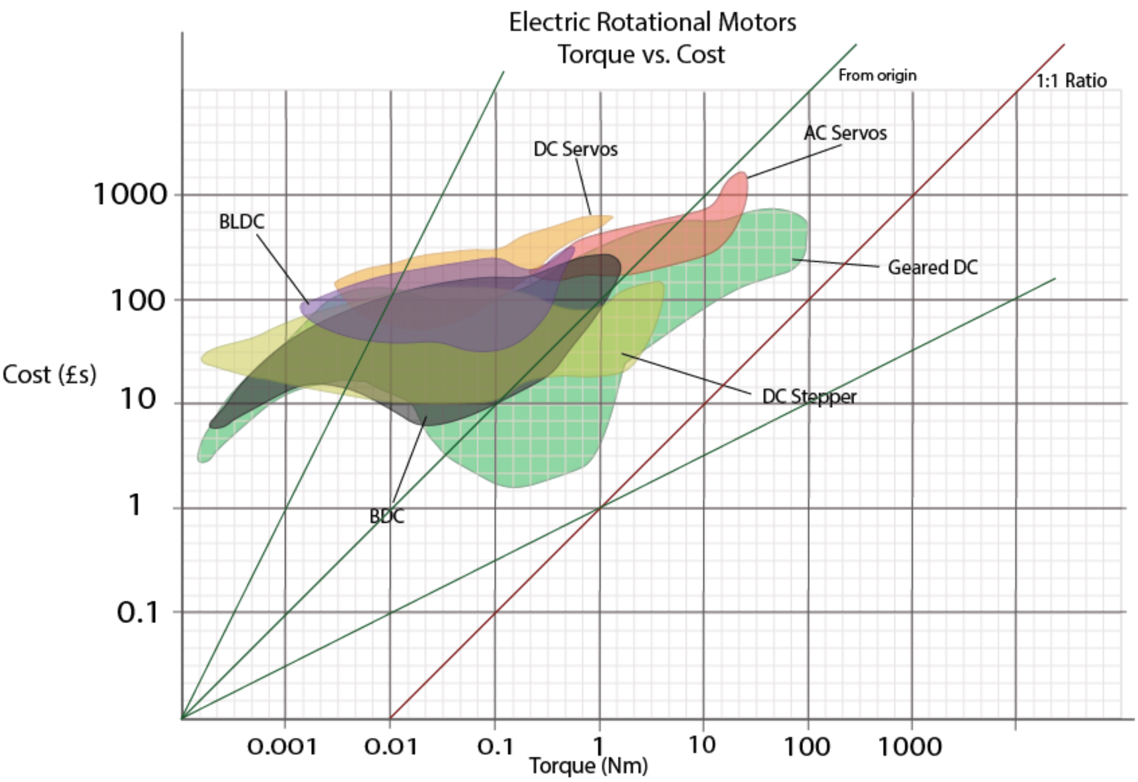

Brakes
Braking Torque vs. Cost
From origin
1:1 Ratio
10,000
1,000
Cost (£s)
100
10
1
Electromagnetic Brakes
Spring-Applied Brakes
Permanent Magnet Brakes
0.1
1
10
100
1,000
10,000
Braking Torque (Nm)

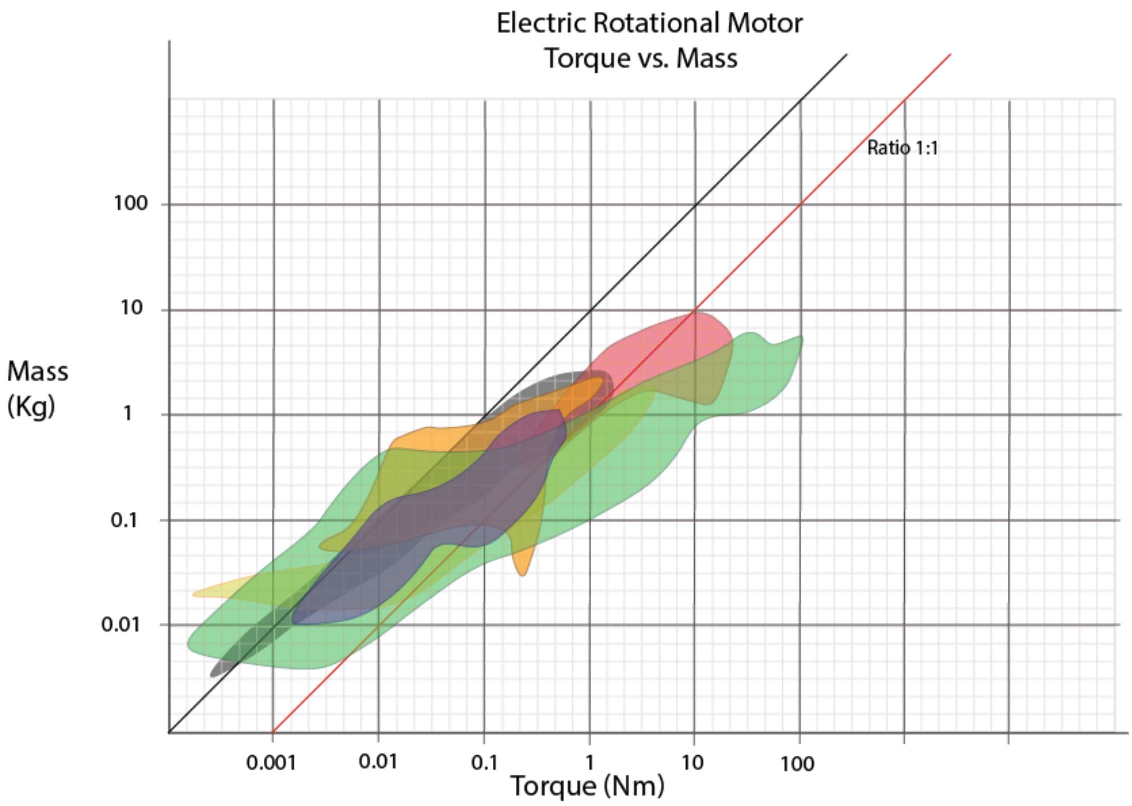

Brakes
Braking Torque vs. Mass
1:1 Ratio
From origin
Mass (kg)
100
10
1
0.1
0.01
Spring-Applied Brakes
Electromagnetic Brakes
Permanent Magnet Brakes
0.1
1
10
100
1,000
10,000
Braking Torque (Nm)

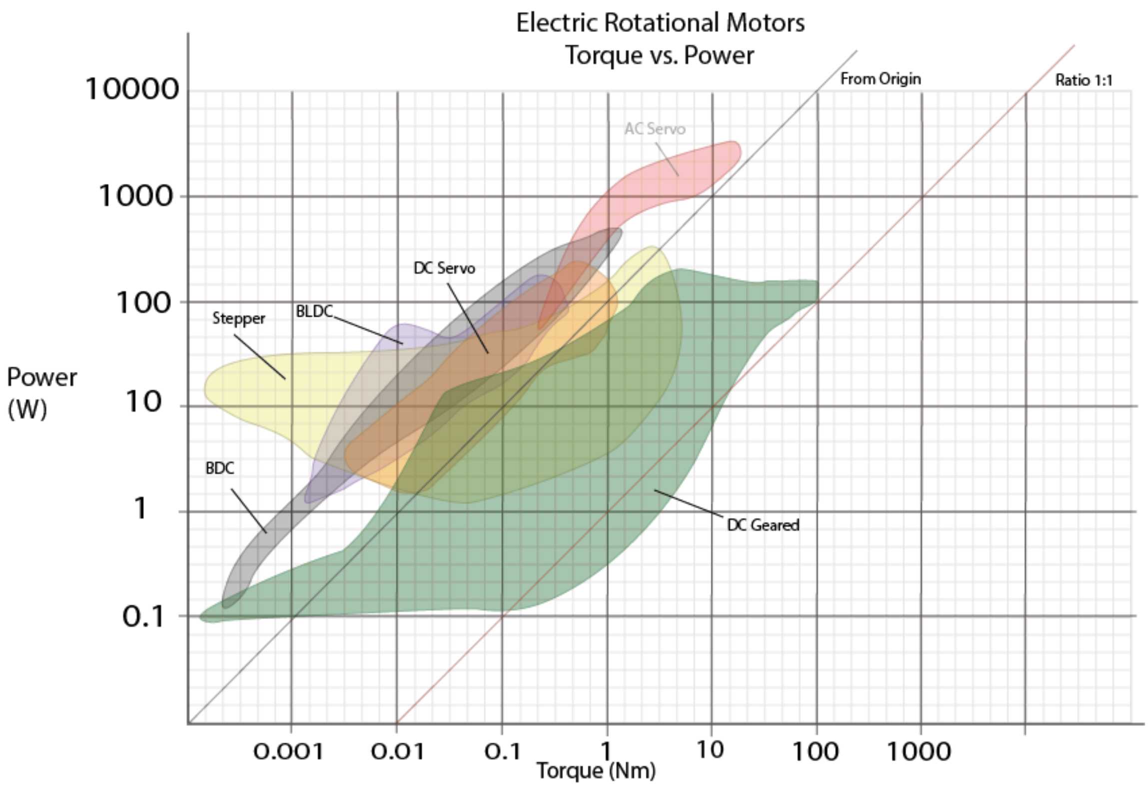

Brakes
Braking Torque vs. Outside Diameter
1:1 Ratio
From origin
Outside Diameter (mm)
1,000
100
10
1
0.1
Spring-Applied Brakes
Electromagnetic Brakes
Permanent Magnet Brakes
0.1
1
10
100
1,000
10,000
Braking Torque (Nm)

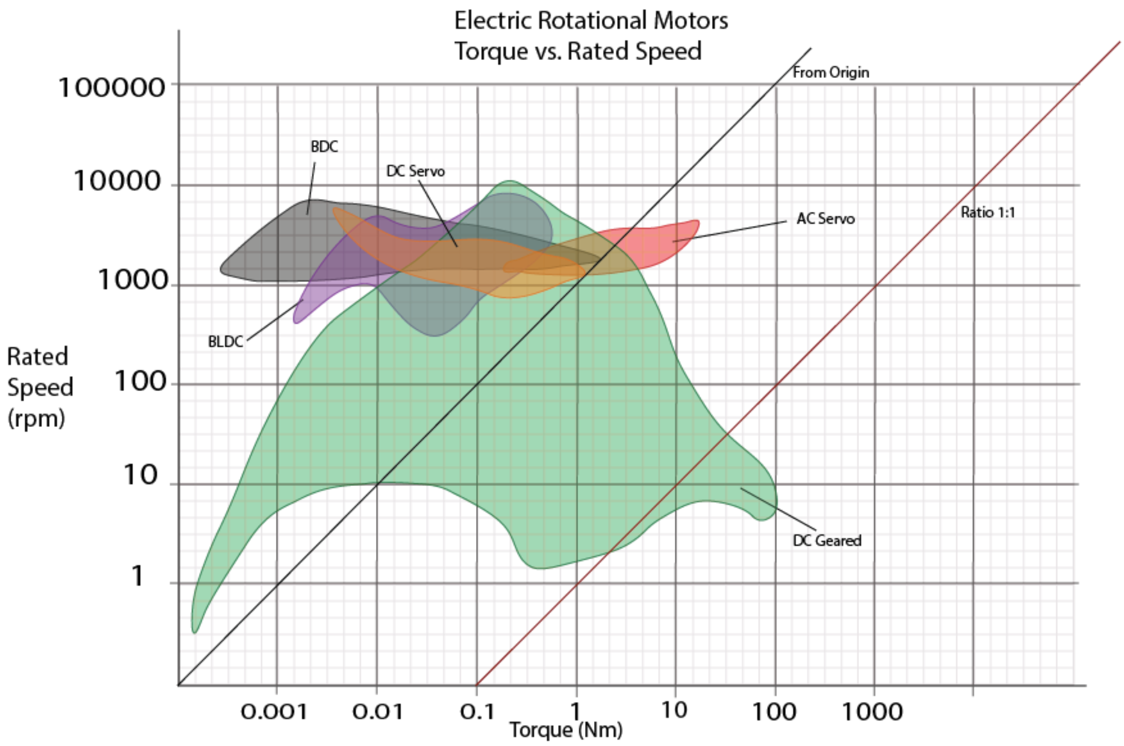


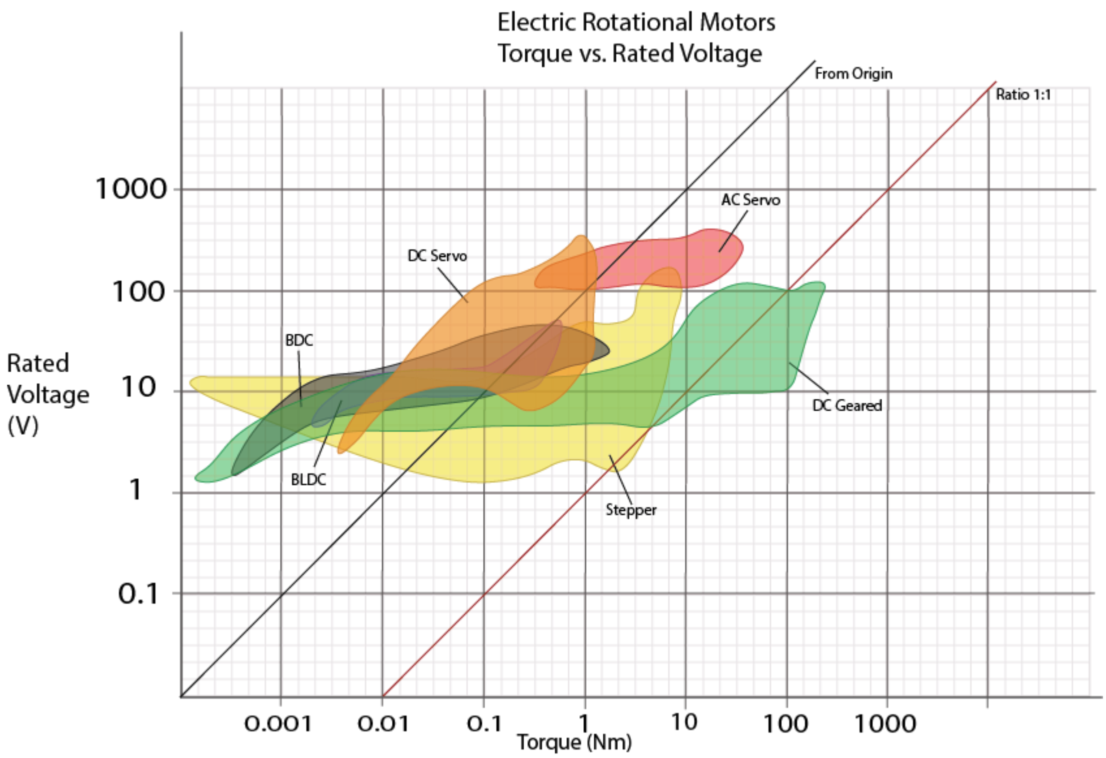
B.2.3. Electric Motors



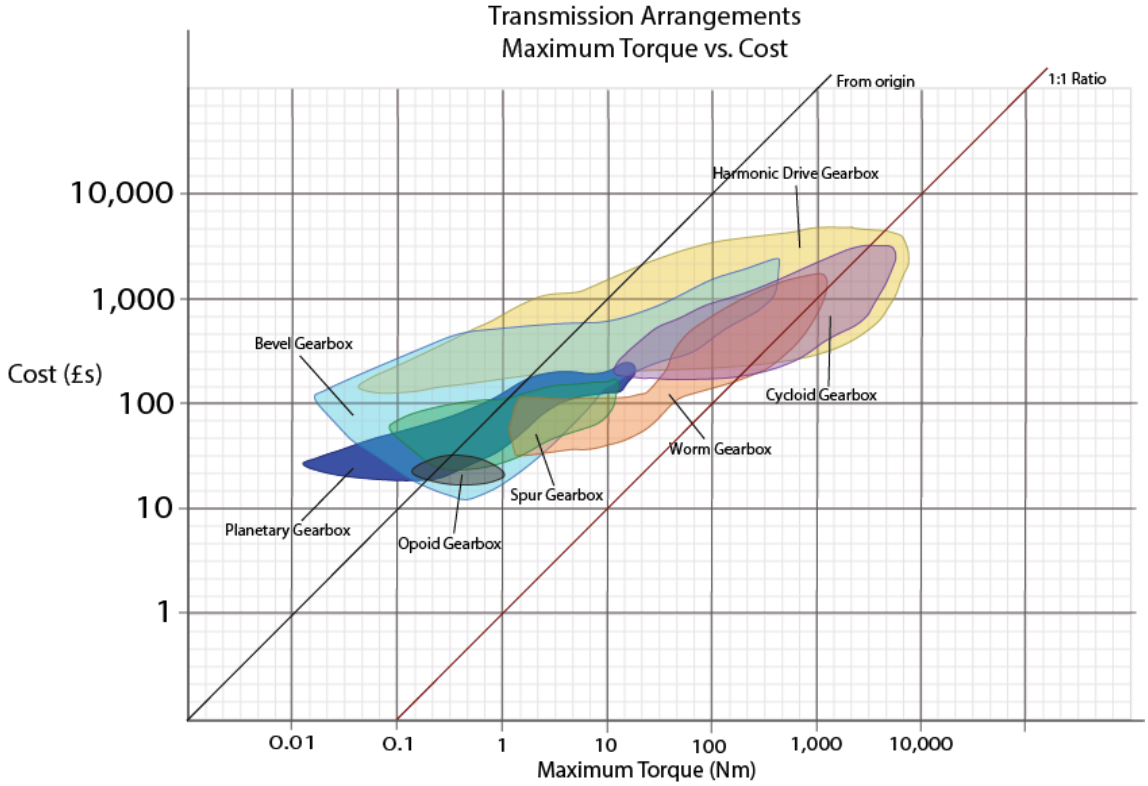

Electric Rotational Motor
Torque vs. Mass
Ratio 1:1
100
10
1
0.1
0.01
Mass
(Kg)
0.001
0.01
0.1
1
10
100
Torque (Nm)

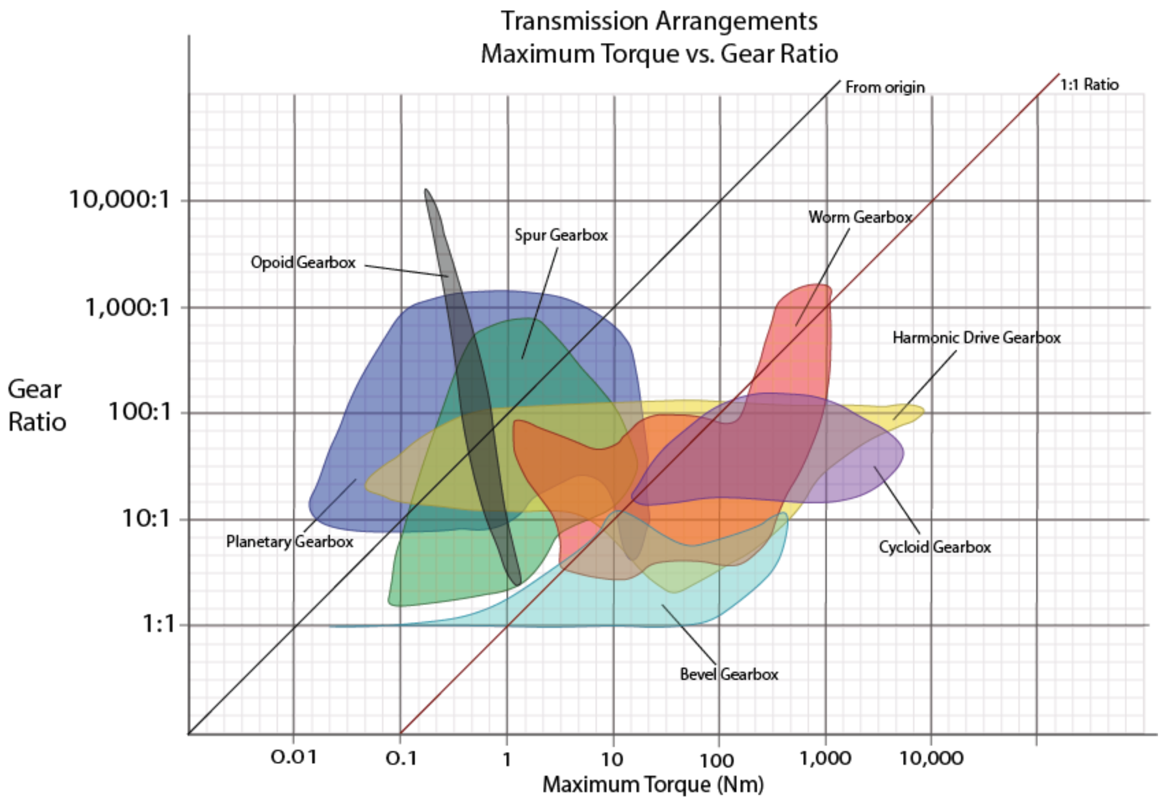

Electric Rotational Motors
Torque vs. Power
From Origin
Ratio 1:1
AC Servo
DC Servo
Stepper
BLDC
BDC
DC Geared
10000
1000
100
10
1
0.1
Power
(W)
0.001
0.01
0.1
1
10
100
1000
Torque (Nm)

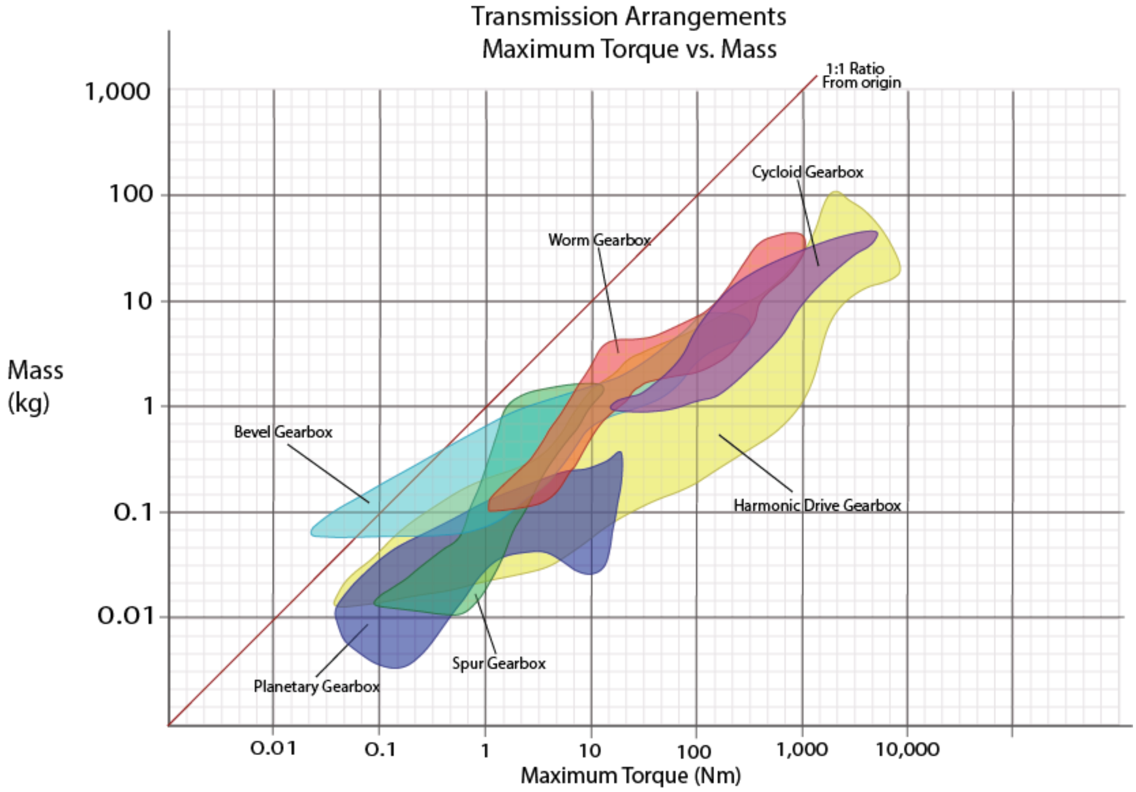

Electric Rotational Motors
Torque vs. Rated Speed
From Origin
Ratio 1:1
BDC
DC Servo
AC Servo
BLDC
DC Geared
100000
10000
1000
100
10
1
Rated
Speed
(rpm)
0.001
0.01
0.1
1
10
100
1000
Torque (Nm)


Electric Rotational Motors
Torque vs. Rated Voltage
From Origin
Ratio 1:1
AC Servo
DC Servo
BDC
BLDC
DC Geared
Stepper
1000
100
10
1
0.1
Rated
Voltage
(V)
0.001
0.01
0.1
1
10
100
1000
Torque (Nm)

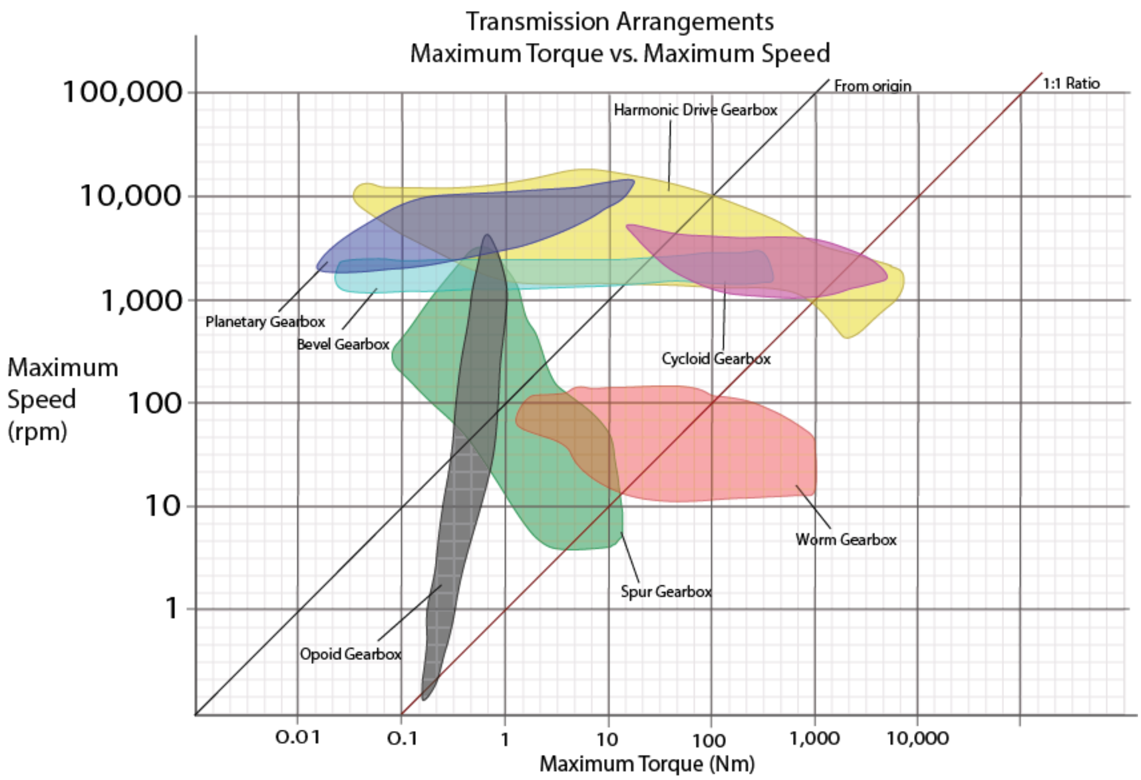
B.2.4. Transmissions







Transmission Arrangements
Maximum Torque vs. Mass
1:1 Ratio
From origin
1,000
100
10
1
0.1
0.01
Mass
(kg)
Cycloid Gearbox
Worm Gearbox
Bevel Gearbox
Harmonic Drive Gearbox
Spur Gearbox
Planetary Gearbox
0.01
0.1
1
10
100
1,000
10,000
Maximum Torque (Nm)



Transmission Arrangements
Maximum Torque vs. Maximum Speed
From origin
1:1 Ratio
100,000
10,000
1,000
100
10
1
Maximum
Speed
(rpm)
Harmonic Drive Gearbox
Planetary Gearbox
Bevel Gearbox
Cycloid Gearbox
Worm Gearbox
Spur Gearbox
Opoid Gearbox
0.01
0.1
1
10
100
1,000
10,000
Maximum Torque (Nm)

B.2.5. Performance Indices for Graphs – Additional Instance

In instances where *B* is positioned below the line the process of deriving the index is *different*, so an alternative algorithm is needed to resolve this.

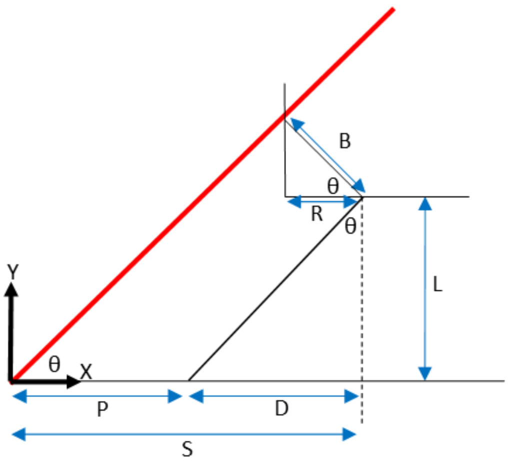


Figure 113: Components utilised in developing a quantitative value for the function-costing index below the index line. X and Y axes denotes, red line indicates From Origin index line.

B is given as:

$$B = \frac{0.5\left[(n_{proportionality} \times S) - (L\ tan\theta)\right]}{cos\theta}$$

This is because:

$$B = \frac{R}{cos\theta}$$

Where,

$$R = 0.5\ \times P$$

S is the value of the '*X*' criteria of the component under consideration; i.e. Torque in example used so far. Therefore, *P* is given as:

$$P = [n_{proportionality} \times S] - D$$

Where *D* is given by:

$$D = L\ tan\theta$$

D does not need the proportionality coefficient applied, as *D* is derived from a Y component; it is already in the correct proportions.

B.3. High-level Taxonomy

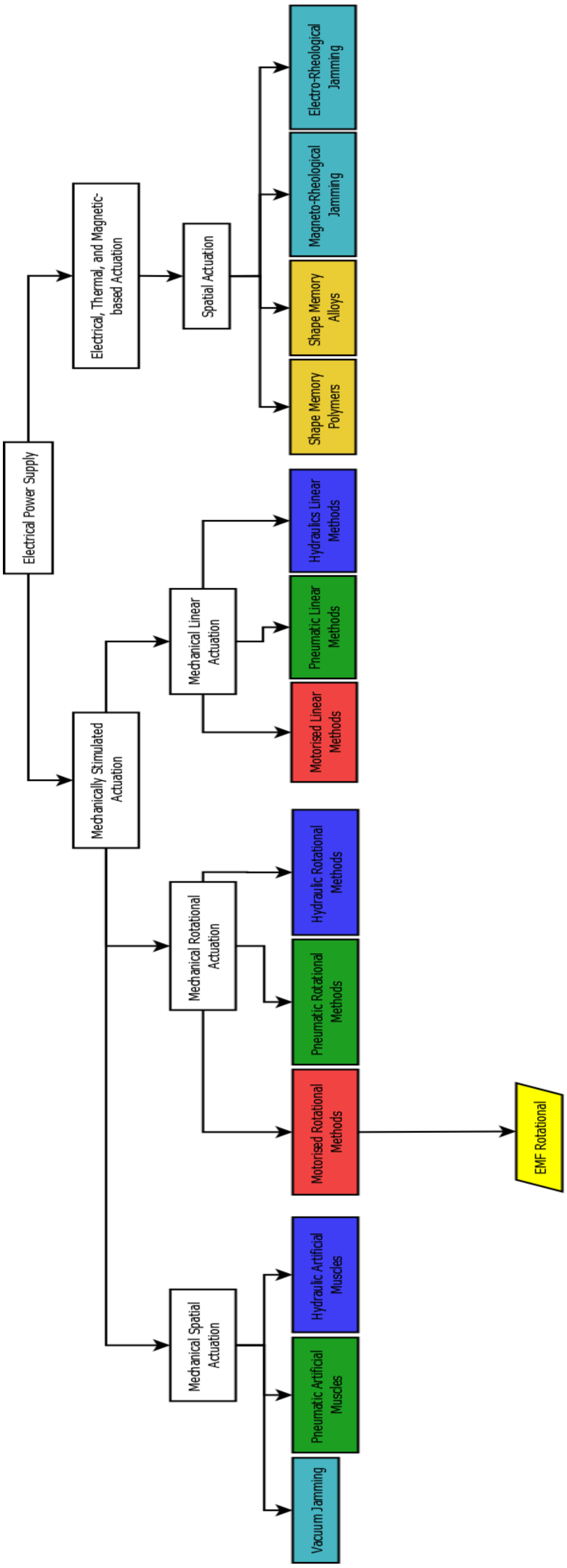


Figure 114: High-level taxonomy of actuation methods.

B.3.1. – Remaining Taxonomies of Component Types

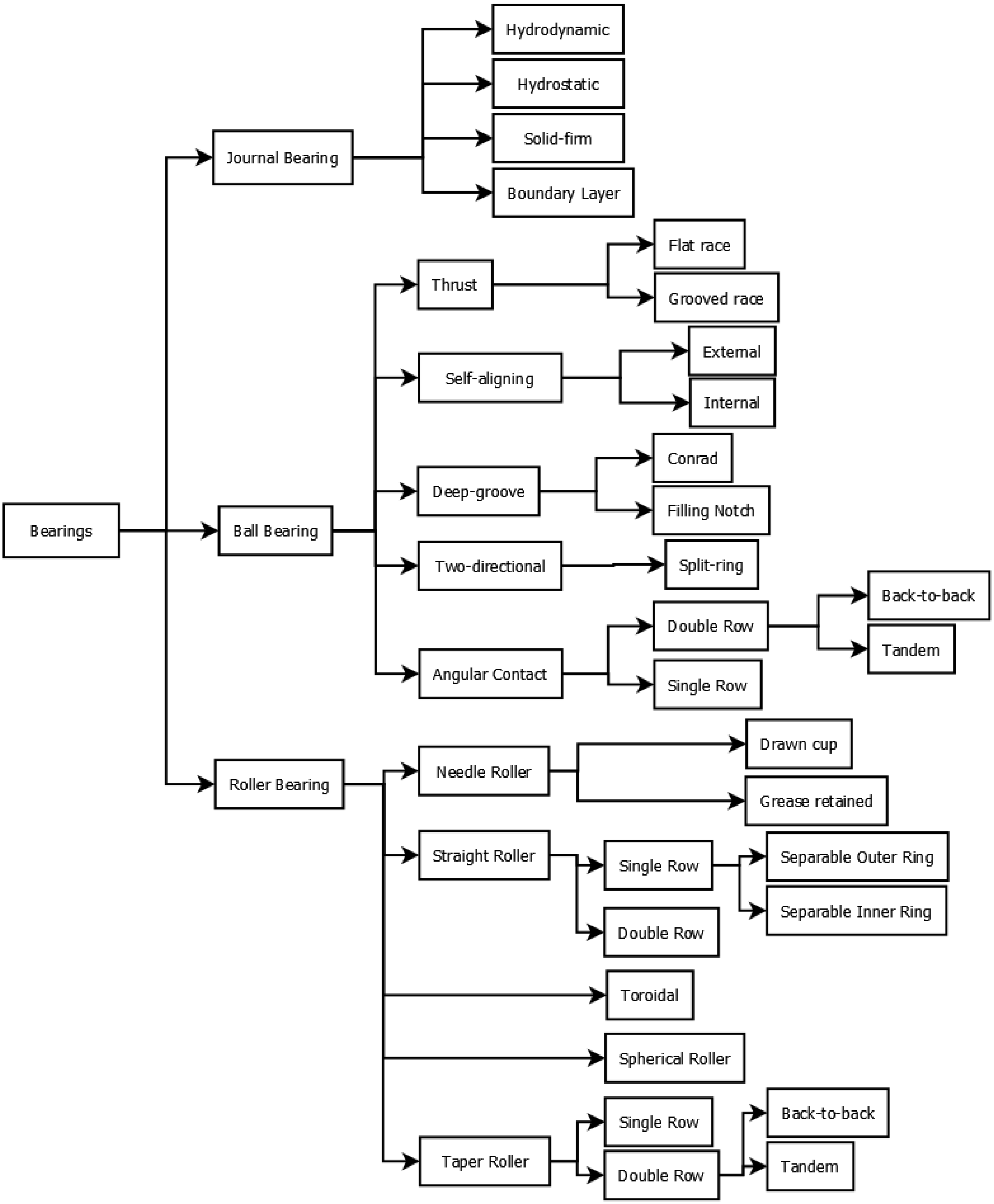


Figure 115: Bearing Hierarchical Taxonomy.

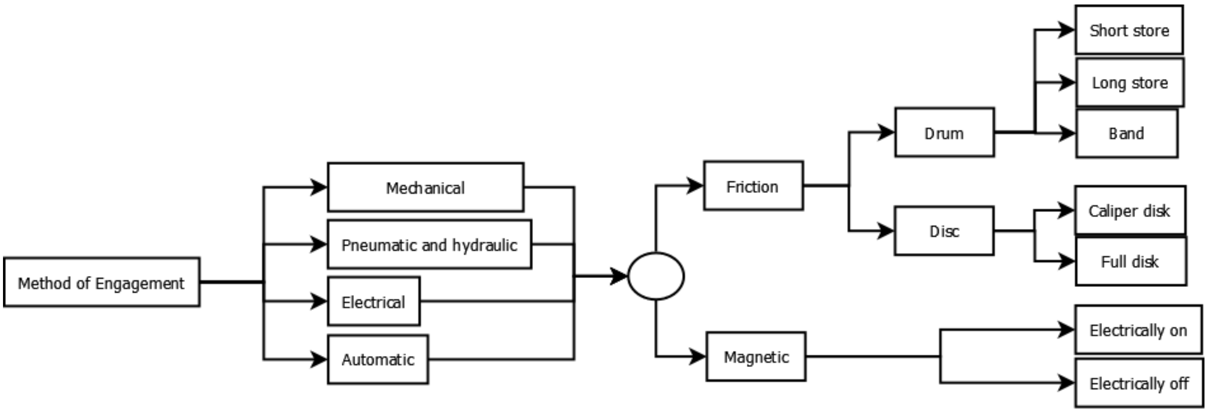


Figure 116: Bearing Hierarchical Taxonomy

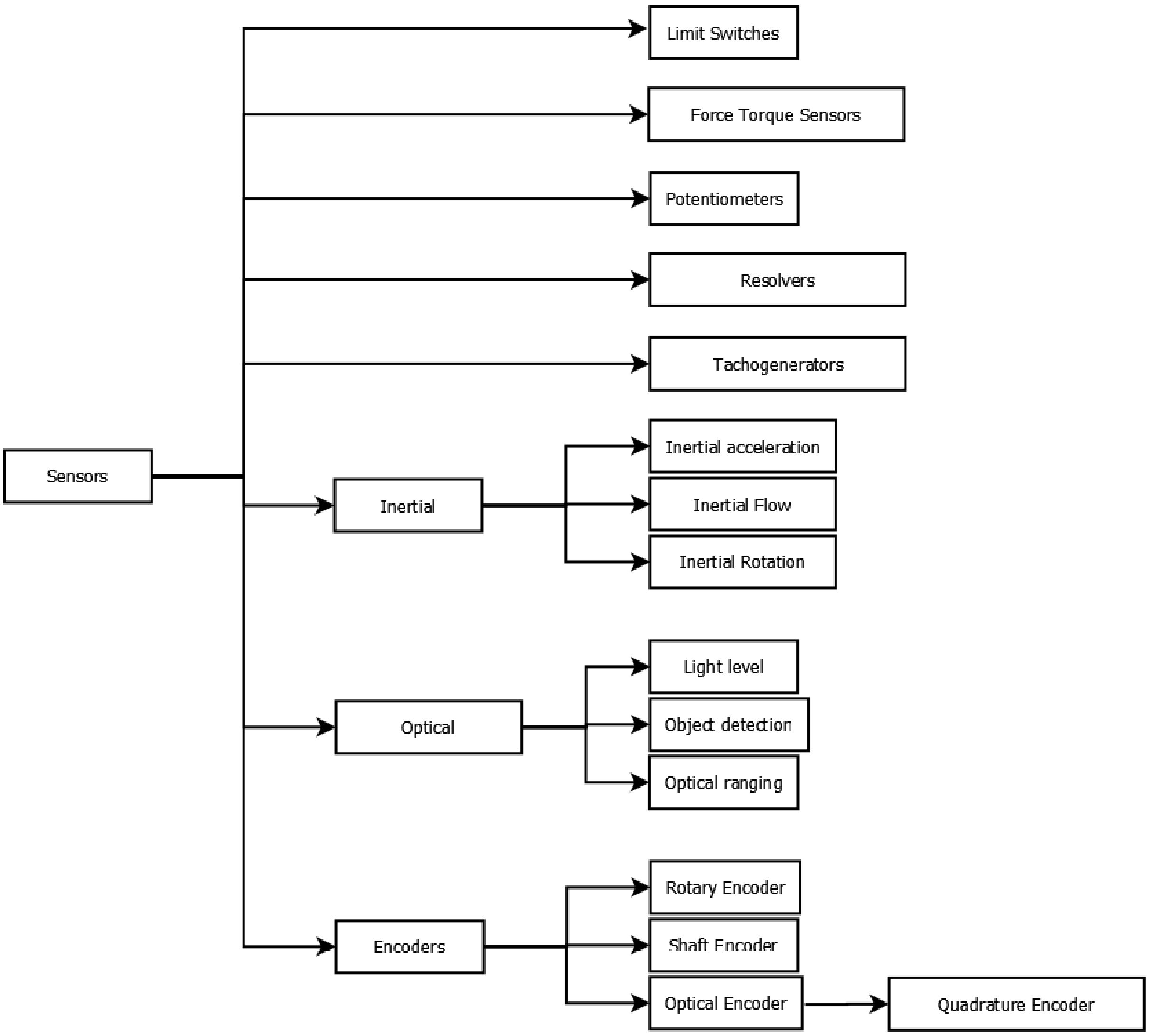


Figure 117: Sensors Hierarchical Taxonomy

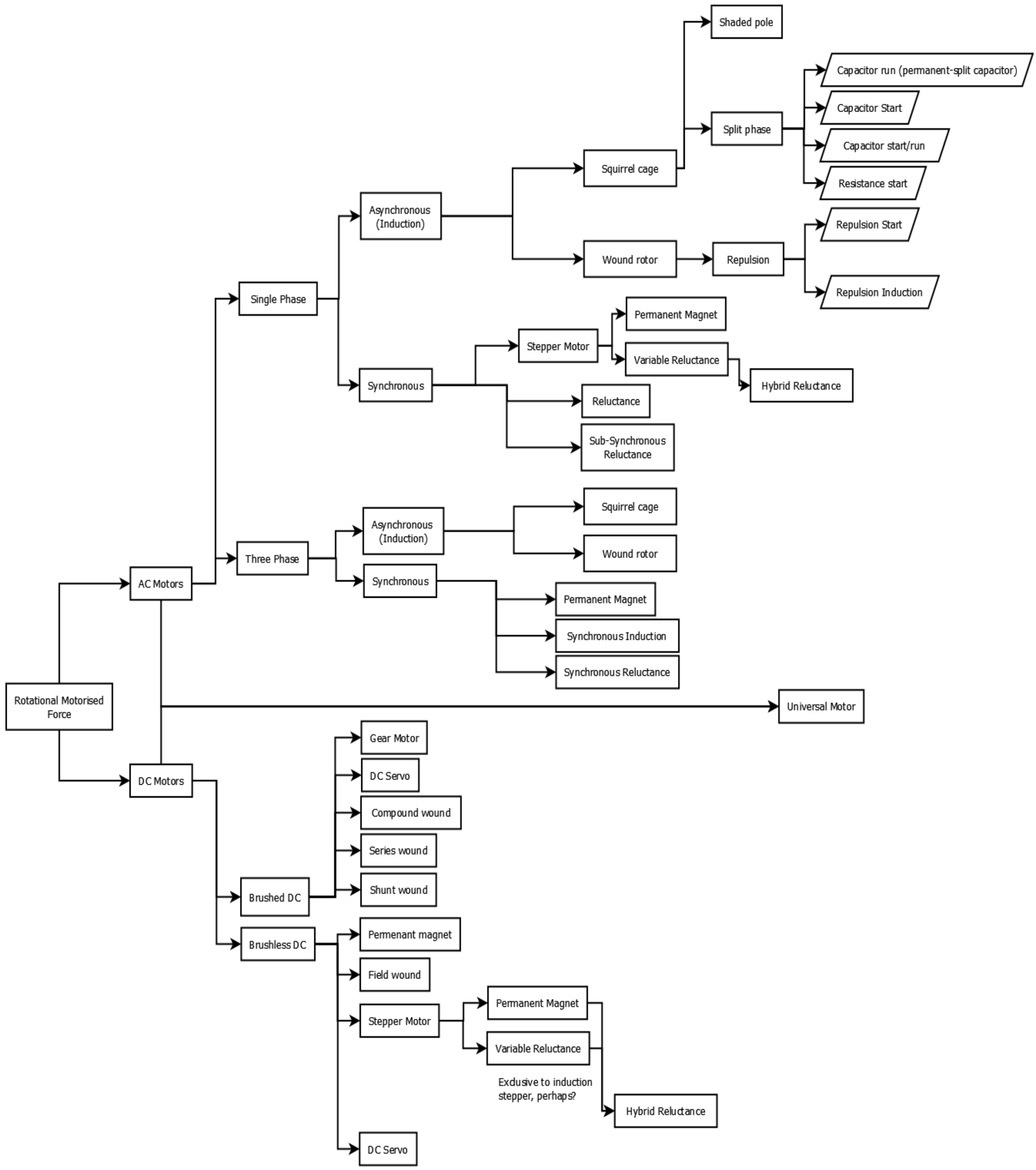


Figure 118: Electric Motors Taxonomy

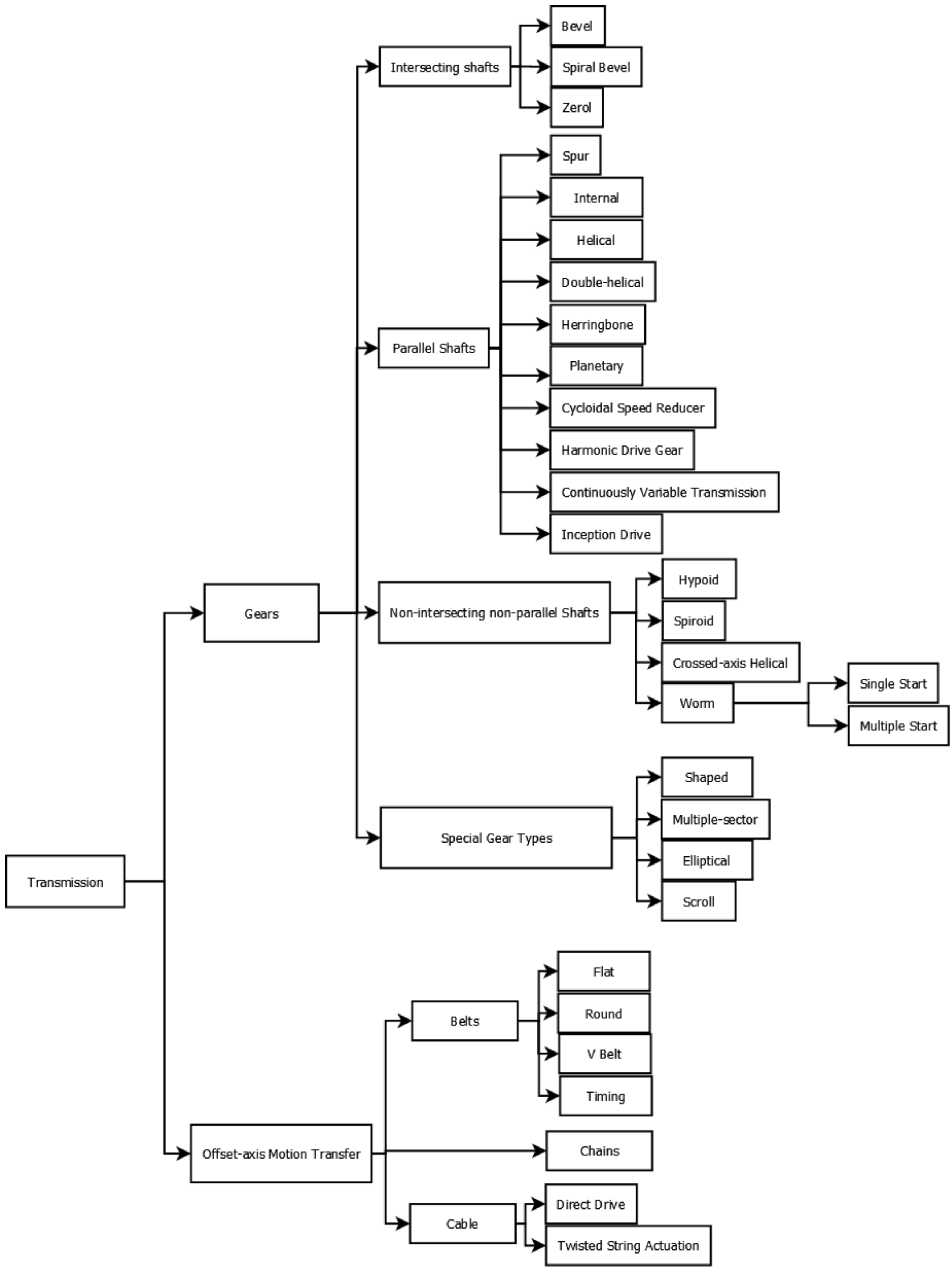


Figure 119: Hierarchical Transmission Taxonomy

B.4. Qualitative Databases

B.4.1. Motors

Table 40: Brushless DC Motor

Issue	Details
Maintenance	• • Less maintenance required; • Generally considered to be highly reliable
Performance	• Known to produce smooth torque, regardless of speed • Higher speed due to no commutation • Good heat dissipation • Low rotor inertia, enabling better acceleration • Generally lighter than BDC motor at same power output level
Typical Uses	• Typically utilised in high speed applications • Often utilised in servo systems

Table 41: Brushed DC Motor

Issue	Details
Maintenance	• Use brushes which typically wear down. Maintenance required depending on frequency of use and application
Performance	• Tend to be higher voltage, as brushes produce voltage drop • Typically run sub-3000 rpm
Typical Uses	• Often used in precision servo systems

Table 42: Stepper Motor

Issue	Details
Maintenance	• N/A
Performance	• Very precise, so long as torque is not exceeded • Exceeding torque can lead to motor being put out of step, meaning inaccuracy is likely if run in open-loop control system • Typical low step angle of 1.8° • Can achieve smaller step angle through process of microstepping • Steps can be heard as clicks, potentially introducing a noise concern • Steps taken quickly; sub-0.1 seconds • High speeds can cause motor to stall due to "slewing" •
Typical Uses	• Ideally suited for open-loop control

Table 43: Geared DC Motor

Issue	Details
Maintenance	• Motor itself comprised of BLDC/BDC motor, so maintenance can depend on motor type used • May be need to maintain gearing, depending on application and type of gear used
Performance	• Inefficiencies due to speed/torque loss in gearing arrangement • Gearing type governs the extent of inefficiencies
Typical Uses	• Can be used in very wide range of applications

Table 44: DC Servo Motor

Issue	Details
Maintenance	• Motor itself comprised of BLDC/BDC motor, so maintenance can depend on motor type used • May be need to maintain gearing, depending on application and type of gear used
Performance	• Specific operation depends on type of motor and sensor used • Closed loop system • Typically comprised of permanent magnet
Typical Uses	• Systems where position control is necessary • Some DC servos come with gearing units installed, so are useful in high-precision, high-torque applications

B.4.2. Transmission (Higher Level Example)

Table 45: Offset Axis Motion Transfer

Issue	Details
Maintenance	• Depends on material utilised
Performance	• Typically used in lower gear ratio set-ups • Good for transfer of motion, less commonly useful in high reduction/increase ratios
Typical Uses	• Instances where transfer is required between two shafts not in alignment • Often between two shafts not in axial alignment, but still parallel with X, Y, and/or Z offset

Table 46: Parallel Shaft Transmission

Issue	Details
Maintenance	• Depends on method utilised. Some types (spur, bevel, etc.) can have issues with wear on gear surface, and wear of bearings.
Performance	• Vast performance range able to be attained – depends greatly on the specific component *type* utilised.
Typical Uses	• Useful in applications where co-axial transfer of motion is needed; • Useful for facilitating high accuracy, low noise, high efficiency, very large gear ratio range, and cost effective solutions also available
Notes	In literature, this type of motion transfer is known as parallel shaft motion transfer. It is suggested that co-axial motion transfer is a better term. As discussed in table 1, shafts can be parallel with an offset and be transferred to. Gear types falling under this heading require accurate alignment between the input shaft and the gearbox shaft, coaxially.

B.4.3. Gearboxes

Table 47: Worm Gear

Issue	Details
Maintenance	• Worm shaft bearings can be subjected to large loads, potentially requiring replacement • Shaft bearings can be subjected to high radial loads, potentially necessitating replacement • Wear can increase backlash, potentially requiring other component replacement
Performance	• Non-backdrivable/self-locking in one direction, which can make for a good safety feature • Minimum backlash options available from some manufacturers • Typically low transmission efficiency • High friction losses due to constant sliding contact • Double enveloping solutions available, which support higher loads
Typical Uses	• Tend to be used in large speed reduction ratios

Table 48: Harmonic Drive Gear

Issue	Details
Maintenance	• Very high quality solution • Not known to deteriorate noticeably in performance over lifetime • Corrosion protection available • Some models come with lifetime precision guarantee
Performance	• Very compact solutions available • Available as gears, with bearings, and in gearboxes/gearheads • Extremely precise over lifetime • Hollow shaft arrangements available • Direct motor connection facilitated • High tilting rigidity
Typical Uses	• Sealed solutions available for use in harsh environments • Available with no flanges, facilitating reduced mass and integrated design • Reduction ratios available are single-stage, making them good for high reduction ratios where maintained efficiency is desired • Used when low backlash needed • Provide a low-mass option

Table 49: Cycloid Gears

Issue	Details
Maintenance	• Minimal wear – similar to HD gears; high contact ratio, so reduced wear • Excellent service life
Performance	• Less than one arc-min of backlash • Very high load capability • Very reliable • Highly efficient • High tilting rigidity • Completely sealed • Compact solutions available
Typical Uses	• Typically used in high-load applications • Particularly useful when long service life, low-backlash, high reliability are needed

Table 50: Bevel Gears

Issue	Details
Maintenance	• High radial and thrust loads on bearings. May necessitate changes
Performance	• Available with augmented tooth arrangements to provide low-noise and smoother operation, where needed • Spiral augmentations available to further reduce noise.
Typical Uses	• Similar applications to spur gear • Often used in right-angled joints/transmission operations

Table 51: Spur gears

Issue	Details
Maintenance	• Tend to have high wear, but this varied depending on ratio and gear sizes
Performance	• Tend to be noisy, especially at high speeds • Where noise and wear reduction is sought, helical gears are a useful option.
Typical Uses	• Used most extensively in moderate speed ranges • Available in internal and external configurations. Internal gears useful when two shafts needs to turn in same direction, mating two external configurations will results in shafts turning in opposite directions • Due to low cost nature, they are used in many household items: clocks, washing machines, etc.

Table 52: Planetary Gears

Issue	Details
Maintenance	• High radial and thrust loads on bearings. May necessitate changes • Multiple contact points, reducing wear • Less stressful on bearings
Performance	• Good speed reducer • Available as single stage or compound arrangements • Generally has quiet operation • In high speed applications, small teeth can reach high temperatures, affecting performance and durability
Typical Uses	• Can be coupled easily with other transmission types to avoid double planetary arrangements

B.4.4. Brakes

EM Brakes

Issue	**Details**
Maintenance	• N/A
Performance	• Draw power when brakes are applied; • Tend to be used where brakes are mostly off since they consume power when applied due to use of electromagnetic solutions to create braking torque.
Typical Uses	• Robotics; • Packaging and food processing machinery; • Medical appliances; and, • Servo motor assemblies.

PM Brakes

Issue	**Details**
Maintenance	• Typically used in applications where
Performance	• Typically heavy due to on-board use of magnets (neodymium, etc.); • Tend to be used when brakes are mostly applied to reduce power consumption as opposed to electromagnetic solutions.
Typical Uses	• Robotics; • Packaging and food processing machinery; • Medical appliances; and, • Servo motor assemblies.

Friction Brakes

Issue	**Details**
Maintenance	• Owing to friction there are issues with wear; • Known to have sporadic failures due to cracking, etc. associated with friction-based application
Performance	• Useful when slowing from high-speeds; • Various maintenance issues, as highlighted
Typical Uses	• Cars, machinery, etc. • Typically utilised where there's a requirement for slowing from a high speed over a moderate period of time; i.e. not instant

B.4.5. Bearings

Ball Bearings

Issue	**Details**
Maintenance	• Owing to single point of contact with spherical balls, damage more likely to occur, especially if used in highly loaded system or run close to MDLR/MSLR • Often damaged bearings need replaced
Performance	• As a general rule, ball bearings are used in higher speed and lighter load applications than roller bearings • Can be instable in certain loading conditions when compared with roller bearings • Can be more expensive initially, but depending on application can be more economical option in the longer run
Typical Uses	• Smooth running applications; • High speed applications; and, • Often in intermittent use, due to better ability to overcome inertia since more friction removed • Better ability to deal with axial and radial loading, especially with variations of alignment

Roller Bearings

Issue	**Details**
Maintenance	• If loading present in a direction the rollers are not calibrated is evident damage can occur • Often damaged bearings need replaced
Performance	• As a general rule, roller bearings are used in higher load and lower speed applications than ball bearings • Rollers have higher contact area than balls, so can be used in higher load applications; • As with other rolling element bearings, can be effective in countering the effects of friction • Due to higher surface area, rolling bearings are known to have better stability • Can be more expensive initially, but depending on application can be more economical option in the longer run
Typical Uses	• Smooth running applications; • High speed applications; and, • Often in intermittent use, due to better ability to overcome inertia since more friction removed • Used typically when loading is focused in either one direction or another; i.e. if load is all/mostly axial or radial, the rollers will be aligned to deal fully with this.

Journal Bearings

Issue	Details
Maintenance	• Designed to wear out rather than damaging shaft they're used on • Available as single or split housing. Split housing is easier to put in place and remove for maintenance
Performance	• Journal bearings often used for heavy applications, as they are better at managing shock and large variance in vibration than rolling element bearings; • Variations of a journal bearing used for smaller applications are often known as sleeves or bushings • Often cheaper in the first instance, but at material wears they can become expensive to maintain.
Typical Uses	• Often seen in heavy machinery with highly-loaded rotating shafts; • Used extensively when applications are non-intermittent

B.5. Analytic Hierarchy Process' Use in Guidelines

The first step of embodiment guidelines require that the Analytic Hierarchy Process is relied upon to create a constructive method of criteria consideration not noted to have previously been applied in component selection in engineering. Objective and subjective methods were considered. It has been outlined that entropy and mean methods are useful in absence of a decision maker, or where their inputs are unreliable (Jahan et al., 2011); however, this is not the case in this instance, so subjective methods based on system requirements are utilised to give the engineer greater control through a formal approach.

Various methods were initially reviewed using key literature reviews (Mela et al., 2012) (Jahan et al., 2011). TOPSIS was initially considered to allow attainment of best alternative (Lai et al., 1994) (Hwang et al., 1993) to ascertain best alternatives using Euclidean from the best/worst solution (Krohling & Pacheco, 2015). Weighted least square (Chu et al., 1979) methods were reviewed, but Analytic Hierarchy Process delivers an *ordered hierarchy* (Saaty, 1990) (Saaty, 2013), which is exactly what is sought, and based on its use in the past in materials selection applications (Jahan et al., 2011) and machine acquisition (Page 710, Nof, 2009) this was considered a solid choice. Modified direct logic has also been applied to materials selection (Fayazbakhsh et al., 2009) and would be an equally useful choice, based on existing uses (Jahan et al., 2011). It was desired to know how criteria *rank* from best to worst, and AHP was considered to achieve this well, so has been utilised in order to achieve this.

Inclusion of AHP allows *targeting* of components which have the criteria which best meets the needs of the system based on a rigorous, hierarchical breakdown of performance needs from an array of components. MCDC for component selection has not been encountered in research for selection of engineering components, but has been used for selection of software components (Verma & Mehlawat, 2017) and is noted for selection of *suppliers* of components (Hague et al., 2015).

Appendix C - Chapter 4 Appendices – Validation Case Studies

C.1. LIGHTWEIGHT ROBOTIC ARM

Document from Original Designers of Arm

DESIGN SPECIFICATION

This document intent to present the necessary changes to be done on the arm design in order to improve its performances and achieve the targets for the project.

General comment

The arm is now 13 Kgs heavy. The arm design was driven by the stiffness because of the initial purposes of the arm. The IRMAP project aimed at using the arm for taking pictures of the crop while the rover runs in the fields. Pictures had to be taken regularly, and therefore it was decided that the arm had to be deployed while the rover ran. It made strict requirement for stiffness in order to reduce vibrations and therefore it had been set a design constrain equal to 0.2 mm per linear meter of arm length. The outer diameters and thicknesses of the links have been chosen in fulfil that requirement. Alluminium reduce the weight compared to a solution with steel.

This being said, the overall arm's weight can be reduce in few ways:

1) replace the aluminium used for the links with carbon/glass fiber composite material. It will raise the cost but reduce the weight of the moving parts while keeping the same stiffness. Lighter links will also reduce the performances required by the motors, which can then be chosen smaller and lighter;
2) reduce the rigidity of the arm. It will allow having thinner links, which will then be lighter and require smaller motors;
3) stop the rover while the arm deploys. In the HAPTIC project the arm is expected to work while the rover stops, and therefore the vibration problem is eliminated: the arm can be made much lighter by reducing its rigidity (which will make the links thinner and smaller, and therefore lighter, and therefore motors can be smaller and lighter with weight saving in most of the parts).

Motors

The motors actually implemented in the arm have been chosen for prototyping-purpose. They are cheap, therefore heavy. Motor 1 (that at the base of the arm) is fine, but Motor 2 and Motor 3 should be replaced.

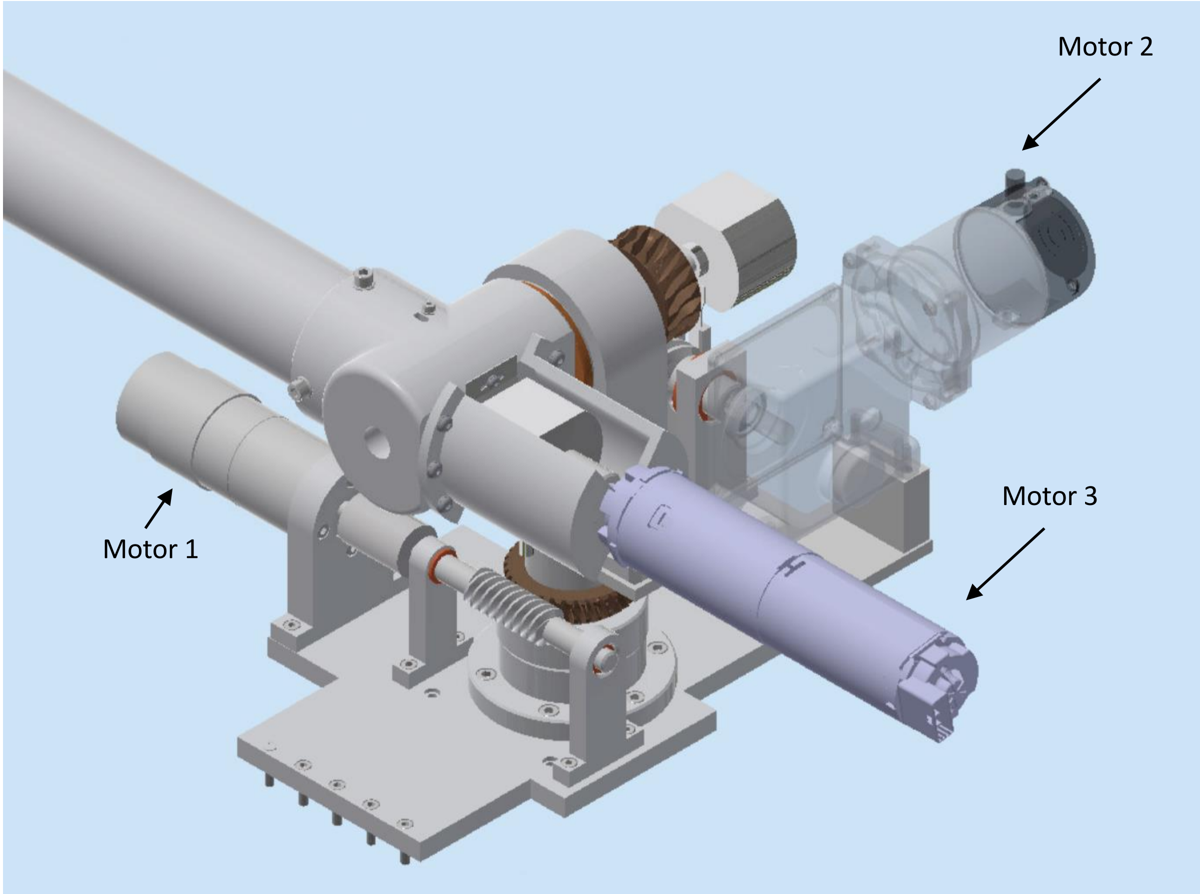


Figure 1: Overall view of the motors.

Two smaller and lighter motors have been identified from Maxon. In particular:

- new Motor 2 will be Motor DCX32L with gearhead GPX37 without encoder (price £ 378.15 + VAT)
- new Motor 3 will be Motor RE 35 part no 323890 fitted to gearhead GP42C 285;1 part no 203133 with encoder part no 110514 and failsafe brake part no 228387 (£ 878.15 + VAT)

HAPTIC project's arm is expected to be lighter, and therefore a new set of motors will be needed.

However the weight of the arm and the type of motors will be, the arm will benefit from having the Motor 3's encoder embedded. It will make the design and the assembly operations much simpler.

Joints

The arm is made of 4 joints, and shown in the figure below.

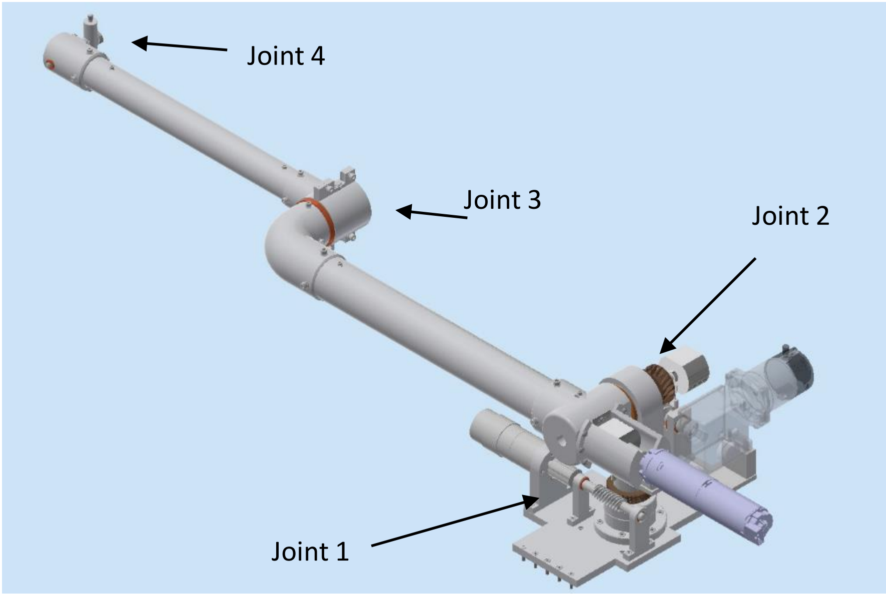


Figure 2: Overall view of the arm and its joints

- Joint 1 and Joint 2 use worm wheels because the arm was expected to stay deployed for long time. Worm wheels are irreversible, and therefore the motors had only to run until the arm reached a certain configuration, which was then fixed by the gears. It allowed powering the motors for a short time, keeping the currency usage very low. The same could not be applied to joint 3 because of there was not enough room.
- Joint 3 and Joint 4 are linearly related. It allows to have only 3 motors for 4 joints. The arm has been designed to reach only two positions, named "Side" and "Top", which allowed to take pictures of the crop from the side and from the top respectively (see picture below).

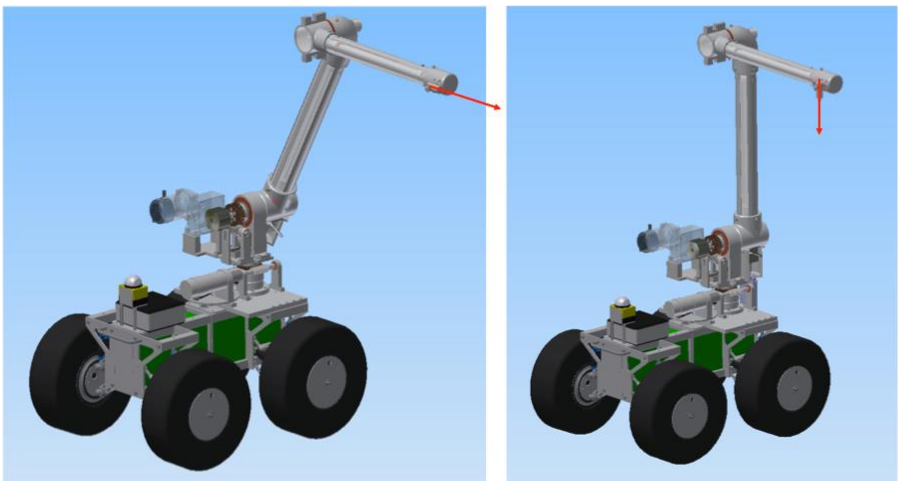


Figure 3: "Side" position (left) and "Top" position (right).

The HAPTIC project will not require the arm standing in a fixed position for long time, and therefore direct drive can be probably used, and joint 3 and 4 will have to be uncoupled.

Bushes and bearings

There are several rotating parts inside the arm, especially inside the links. Since the arm was not expected to run for long (as mentioned before it had only to reach a certain configuration and then keep it for long time) several bushes have been used. For the HAPTIC project the arm will have to move longer, and smoother, therefore the bushes shall be replaced with bearings.

Design improvement required

The arm in its current state works quite fine. What shall be improved is Joint 3. As shown in the picture below, the link 2 is actuated by a couple of gears.

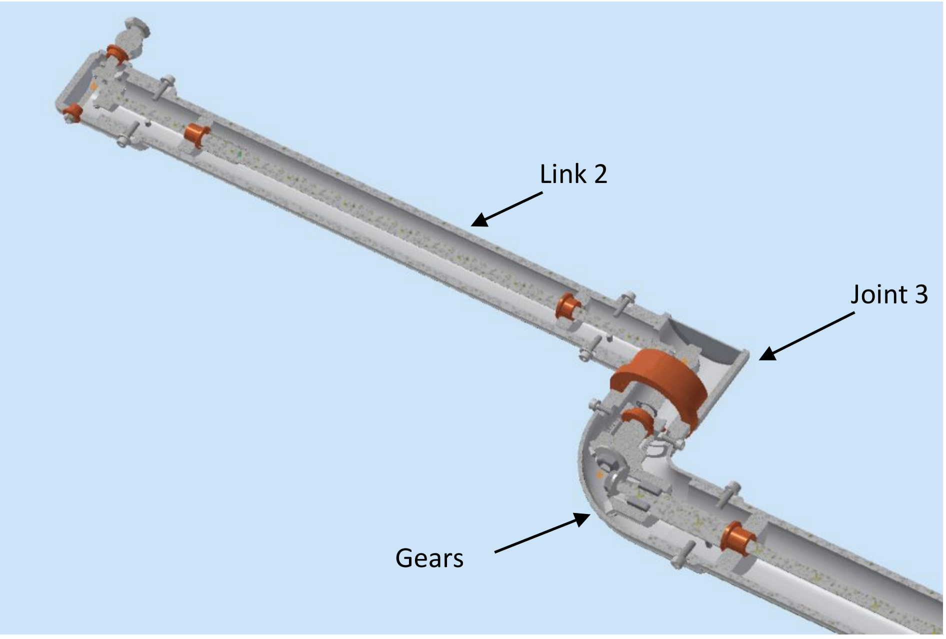


Figure 4: Section view of Joint 3

The gears causes the link 2 to have a large undesired backslash, which voids the stiffness requirement mentioned above. In order to mitigate that effect, a torque spring can be introduced into the joint and gears shall be replaced whit larger number of teeth ones; eventually a review of the design of the joint is desirable.

HAPTIC features

The arm in its current status is not designed for HAPTIC features. All the joints have been designed for 360 degrees of rotation (Joint 2 can not, but with few changes it would be possible), and it is not likely to happen in an HAPTIC control.

The use worm gears, is also probably not desirable because of their irreversibility; direct drive is preferable for faster and smoother control.

C.2. Existing Components

There are 3 actuators in the Agribot arm assembly. Relative to the interests of the framework, the components they contain are in tables below.

Table 53: Components used in Agribot joint 1.

Component	Model
Motor	MFA Comodrill 975D1041
Transmission	HPC SWH1.5-4 & M1.5-35
Bearings	SKF 61908-2RZ

Table 54: Components used in Agribot joint 2.

Component	Model
Motor	Maxon DCX32L + GPX 37 gearhead
Transmission	HPC SWH2-4 & M2-20
Bearings	SKF 626-RS1

Table 55: Components used in Agribot joint 3.

Component	Model
Motor	Maxon RE35
Transmission	HPC P20-60
Bearings	SKF 63003-2RS1
Brake	Corbetta DFM 080

C.2.1. AHP Process

The process begins by establishing the *most* crucial criteria for each component. Numbers assigned during pair-wise comparison are derived implicitly from the design specification document. The whole process is available to review in appendices; however, the example for motors is given below:

Table 56: AHP Use.

Criteria Weights	0.33	0.14	0.08	0.10	0.28	0.05	0.02				
	Torque	Speed	Cost	Mass	Stall Torque	Power	Voltage		Weighted Sum Value	Criteria Weights	Ratio
Torque	0.33	0.42	0.40	0.50	0.56	0.25	0.18		2.64	0.33	8.00000000
Speed	0.11	0.14	0.24	0.30	0.06	0.15	0.10		1.10	0.14	7.82857143
Cost	0.07	0.05	0.08	0.03	0.06	0.15	0.14		0.57	0.08	7.15000000
Mass	0.07	0.05	0.24	0.10	0.07	0.15	0.10		0.77	0.10	7.72666667
Stall Torque	0.17	0.70	0.40	0.40	0.28	0.25	0.14		2.34	0.28	8.33928571
Power	0.07	0.05	0.03	0.03	0.06	0.05	0.06		0.34	0.05	6.77333333
Voltage	0.04	0.03	0.01	0.02	0.04	0.02	0.02		0.17	0.02	8.63809524
										sum of ratios	54.46
										λmax =	7.78
										Consistency Index	0.13
										Consistency Ratio	0.0984000

$$\lambda_{max} = \frac{8 + 7.83 + 7.15 + 7.73 + 8.34 + 6.77 + 8.64}{7} = \frac{54.46}{7} = 7.78$$

Where *n* is the number of criteria under consideration, in this instance 7:

$$Consistency\ Index = \frac{\lambda_{max} - n}{n - 1} = \frac{7.78 - 7}{7 - 1} = \frac{0.78}{6} = 0.13$$

For 7 components in a matrix of this ilk, the random index (R.I.) = 1.32, therefore:

$$Consistency\ Ratio = \frac{C.I.}{R.I.} = \frac{0.13}{1.32} = 0.0984$$

In first application, robustness issues were encountered due to the consistency ratio being above the threshold (0.1) specified (Saaty, 1990). The process was reviewed and an acceptable value was achieved, enabling weighting information provided to be utilised.

Table 57: Priority for consideration of motors.

Criteria	Weight	Priority
Torque	33%	1
Speed	14%	3
Cost	8%	5
Mass	10%	4
Stall Torque	28%	2
Power	5%	6
Voltage	2%	7

C.3. Issue with Disparity in Graph

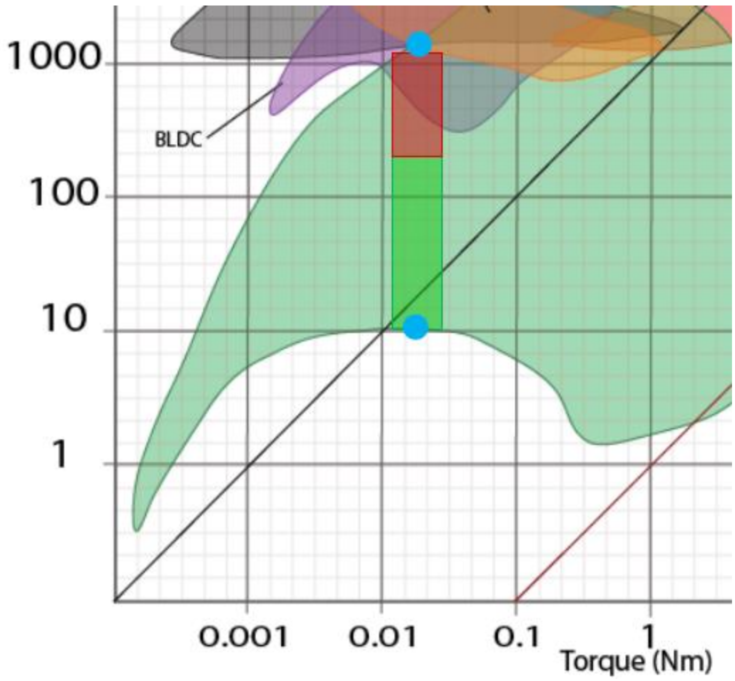


Figure 120: Red box highlights the discrepancy in the graph's representation of speed against torque for geared DC motors at the specified torque value.

The red box represents where the issue lies, whilst the green box with black borders (for clarity) represents speed range available at the 0.018 Nm range.

C.4. Comparison of New Components to Old Components

C.4.1. Joint 3

C.4.1.1. Transmission

Comparison of the transmissions selected is provided below:

Table 58: Comparison between the component selected and that used originally.

Criteria	HPCP20-60	HPCP20-60
Maximum torque	4.1 Nm	4.1 Nm
Speed	6000 rpm	6000 rpm
Cost	£123.50	£123.50
Mass	0.18 kg	0.18 kg
Gear ratio	60:1	60:1

C.4.1.2. Alternative Transmission – Omitting Mechanical Design Requirement

Due to the nature of the selection process carried out (i.e. sparsity of worm drives available and replication of component originally selected), selection has also been undertaken to select for greatest mass reduction possible. This component would allow the mass to be reduced significantly where a new mechanical set-up for the mounting of the motor and gearbox was to be sought. The result is given in table 59.

Table 59: Comparison of an alternative component selected and the initial component selected.

Criteria	HPCP20-60	Maxon 110339
Maximum torque	4.1 Nm	**1.4 Nm**
Speed	6000 rpm	6000 rpm
Cost	£123.50	£123.91
Mass	0.18 kg	**0.068 kg**
Gear ratio	60:1	**84:1**

Comparisons of the two gearboxes considered show negligible cost and speed variation, but that the 110339 has a more appropriate torque capability and is almost 3x lighter than the HPCP20. In terms of the priority criteria developed through the AHP process for transmission, it can be seen that mass has higher precedence than cost and gear ratio. Higher priority in this case study is maintaining mechanical design similarity, hence omission of this specific component.

Comparisons of the two gearboxes considered show negligible cost and speed variation, but that the 110339 has a more appropriate torque capability and is almost 3x lighter than the HPCP20. In terms of the priority criteria developed through the AHP process for transmission, it can be seen that mass

has higher precedence than cost and gear ratio. Higher priority in this case study is maintaining mechanical design similarity, hence omission of this specific component.

C.4.1.3. Brake Selection

A brake is utilised in joint 3 as a failsafe, and as a means to account for a planetary gearbox potentially being used in future designs. This must be capable of dealing with the loading conditions; 1.261 Nm. To ensure that the arm will not fail, a larger factor of safety will be applied to deal with >2.5 Nm.

The main issue encountered has been raised by the qualitative database. In the initial design, an electromagnetic power-on brake was utilised, but qualitative review highlighted that brakes of this nature pull power at all times when the brake is applied. Since the system being designed would have the brake applied >90% of the time, this constitutes a poor choice in terms of draining the system's battery. Instead, a power-off brake is suggested as being more suitable. Graphs have again provided ample capacity to support selection, yielding the result discussed on the following page.

The Corbetta PMB 075 represents a component which is the best suitor for the task at hand. When contrasted with the solution already selected it can be seen how it compares, below:

Table 60: Comparison of brakes utilised in first iteration and with framework. Framework solution in green.

Criteria	Corbetta 080 DFM	Corbetta PMB 075
Braking torque	7.5 Nm	**5 Nm**
Mass	0.28 kg	0.3 kg
Cost	£120	£212
Power	11.5 W	**9 W**
Outside Diameter	0.080 m	**0.075 m**

As outlined already, the component used initially was a poor choice for other reasons, so this comparison is somewhat of a red herring. It is slightly heavier, and £92 more expensive than the solution that had already been in place.

The order of precedence defined by AHP ranks mass ahead of power for the brake, but by only ~4% weighting; i.e. they are somewhat comparable. Additionally, the reason mass is important in this design task is to reduce the torque and therefore the power drawn by components operating the system, as the arm will be battery operated. A negligible increase in mass has been allowed in order to make a *substantial* power saving. This further demonstrates that the guidelines can be deviated from where necessary if an over-riding issue is encountered.

As outlined, power will be drawn by the 080 DFM >90% of the time, whilst the opposite is true for PMB 075 facilitating a huge power saving. This framework could arguably have stopped this issue occurring in the first instance by flagging this crucial qualitative piece of information on EM brakes' functionality.

It is also worth noting that brakes are less readily available, therefore the sample size from RS components and a handful of other suppliers/manufacturers rendered a less diverse sample from which to choose components from. Sampling was not undertaken rigorously purely to ensure that this component **would** be lighter, whereas the engineer designing the system would presumably have spent effort trying to find the best component available. The component selected actually has a higher braking torque than is desirable. That is to say, with a more exhaustive database from which graphs to be built, it is extremely likely that a more appropriate braking torque could be found, and therefore an even lighter and more power effective solution could have been found.

The framework has again facilitated selection of an appropriate component. It is accepted that the extent to which it is "better" than the original component can be contested.

C.4.1.4. Bearing Selection

The process is similar to as stated above, but the process for bearing selection is covered in the appendices in the interests of avoiding repetition. Quantitative selection aided in choice between roller and ball bearing, whilst quantitative overview allowed understanding that journal bearings are not suitable for this application The bearing eventually selected is a RS Pro 619-0014, which is cheaper and lighter than the original bearing utilised.

C.4.2. Joint 2

C.4.2.1. Motor

To prevent further repetition of similar themes, the component selection for joint 2 is summarised below:

Table 61: Motors used comparison.

Criteria	**Maxon DCX32L + GPX 37**	**E192-12-5**
Torque	20.6 Nm	0.2 Nm
Cost	£397	**£54.27**
Mass	0.735 kg	**0.385 kg**
Voltage	12 V	12 V
Power	110 W	**21 W**
Speed	28.4 rpm	**510 rpm**

C.4.2.2. Gearbox

Table 62: Comparison of transmission systems from selection by graphs and from original design.

Criteria	**HPC SWH2-4 & M2-20 & custom shafts,**	**HPC P40-60**
Torque	79 Nm (includes inefficiency)	18 Nm
Cost	>£300	**£207.03**
Mass	~0.5 kg	0.92 kg
Gear Ratio	5:1	60:1
Speed	50 rpm	5 rpm

The original configuration for joint 2 ran a DC motor into a worm drive. The components used were not low backlash variants, so the transmission was blighted with a large backlash problem. Awareness of backlash-free variants is raised in qualitative review, meaning this was able to be understood. The HPC SWH2-4 & M2-20 are gear wheels, not a gearbox. This also contributes to issue around weight, as it is not a direct comparison. The solution selected is low-backlash, so is expected to be firmly more effective in performance.

The alternative components proposed provide a better specified set of solutions and constitute a means by which power might be transferred in a better manner. The solution provided is lighter, cheaper, more energy efficient, and is considered to be more appropriate for the task needed.

The bearing selected to be used in this is an NSK 6206DDU, providing a sealed bearing which is appropriate for the types of environment that the system might find itself in.

C.4.2.3. Bearings

Table 63: Comparison of bearings.

Criteria	**SKF 61908-2RZ**	**NSK 6206DDU3**
Max. Static Load Rating	10 kN	**11.3 kN**
Max. Dynamic Load Rating	13.8 kN	**19.5 kN**
Cost	£40.52	**£10.66**
Mass	0.2 kg	**0.199 kg**
Outer Diameter	62 mm	62 mm
Inner Diameter	30 mm	30 m

C.4.3. Joint 1

The transmission system of joint 1 is embedded into the physical design of the robot arm; see figure 70. This transmission will be unchanged, since changing would require significant redesign. There is also a concern that funds may not be available to allow physical manufacture and assembly of this joint, which then risks physical testing of the whole system. 3D printed assembly components may have failed under the load conditions. Ideally, this transmission would have been replaced, as the transmission is laden with several issues.

C.4.3.1. Motor

Table 64: Comparison of motors utilised in joint 1.

Criteria	**MFA Comodrill 975D1041**	**McLennan 16HS-012**
Torque	3.72 Nm	0.087 Nm
Cost	£52.78	£83.89
Mass	0.632 kg	**0.15 kg**
Voltage	12 V	12 V
Power	41.3 W	**7.2 W**
Speed	67 rpm	**1.8° Per step**

The motor selected is a stepper motor, allowing the system to run with open-loop control. With this capability the system can be tested without an optical encoder and one added latterly, if required. This would allow the system to function without the need an encoder, justifying the higher price. Additionally, it can be seen that there is a large difference in mass and power requirements of the two motors. If the system is able to function correctly, then a substantial mass saving will have been gained.

C.4.3.2. Bearings

Table 65: Comparison of bearings selected for use in joint 1.

Criteria	**SKF 61908-2RZ**	**NSK 6206DDU3**
Max. Static Load Rating	10 kN	**11.3 kN**
Max. Dynamic Load Rating	13.8 kN	**19.5 kN**
Cost	£40.52	**£10.66**
Mass	0.2 kg	**0.199 kg**
Outer Diameter	62 mm	62 mm
Inner Diameter	30 mm	30 mm

C.4.3. Wiring of Agribot Arm

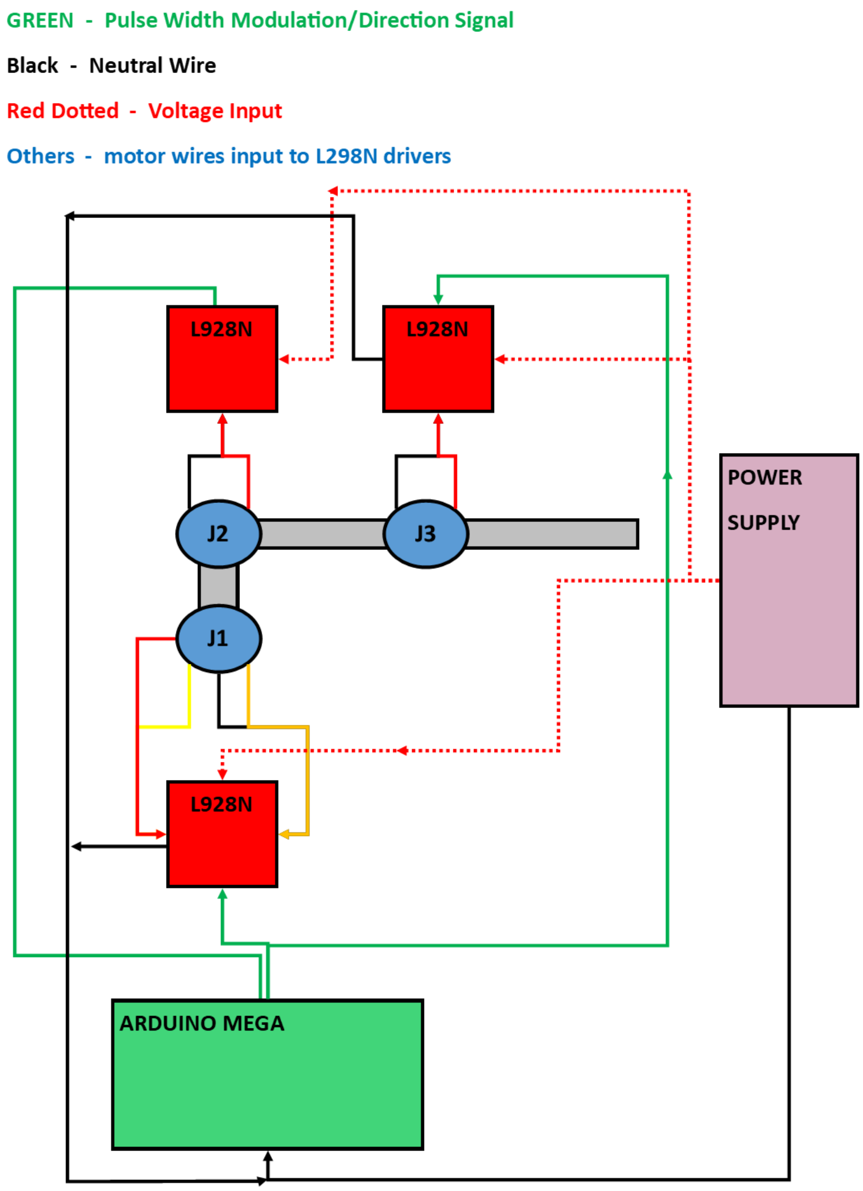
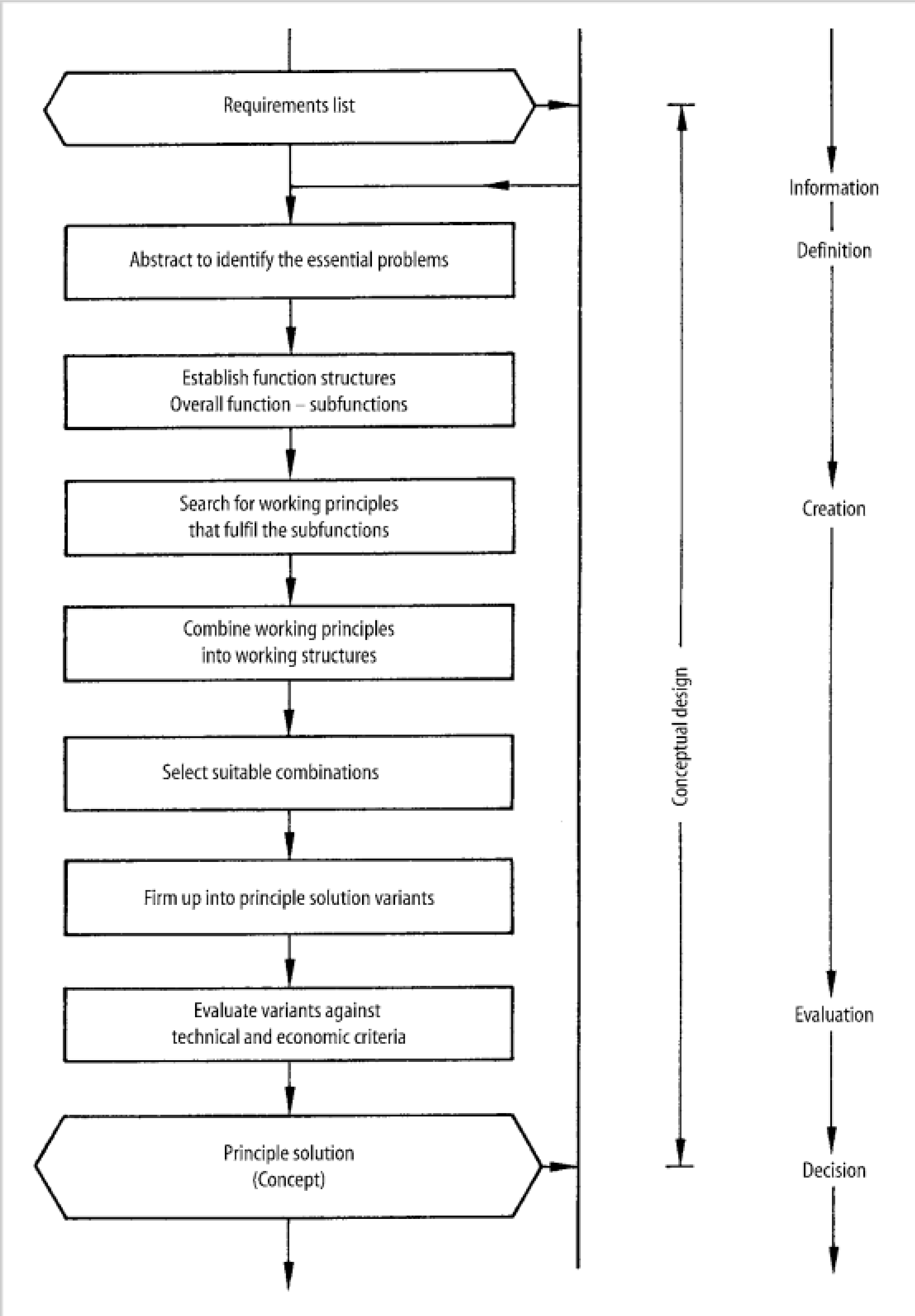


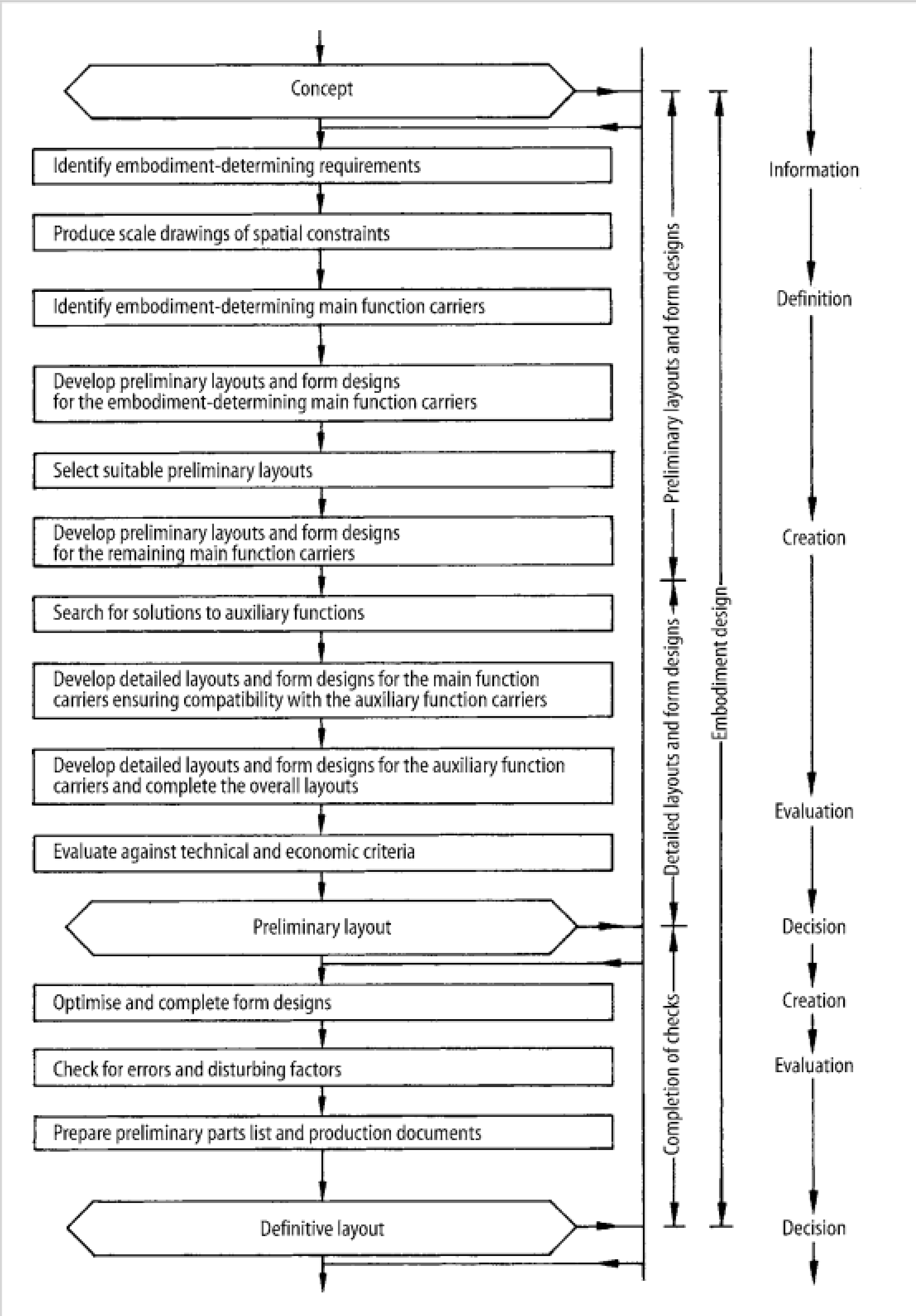
Figure 121: Wiring for Agribot Arm.

Separate L298N motor drivers have been used to control each individual geared motor, and an additional L298N was used to control the stepper motor. An Arduino Mega has been utilised to program motors and brake, and provided a platform to integrate the existing optical encoders also. An external power supply has been used to power each of the L298N drivers, whilst power for the Arduino board has taken from the laptop input where the Arduino IDE has been utilised for system control. New components are accommodated in 3D printed joints housings; previous joints were tailored to old components, so mating flanges available were not suitable for mounting new components.

C.5. Case Study 2 – Concept Level Steps by Pahl and Beitz



C.6. Case Study 2 – Embodiment Level Steps by Pahl and Beitz



C.7. Overview of the Design Task in Case Study 2

A new, experimental actuation package will be developed for extrinsically actuated, cable-driven continuum/tensegrity systems. Applying this framework to this task will test the versatility of the approach to component selection, as well further evaluating application generally. Several elements will be assessed in case study 2, summarised as:

a) Further review of the framework's performance, to better understand its application in differing use case;
b) Developing understanding of the framework with well-established engineering design methodologies, allowing understanding of *where* in the process the framework is likely to be useful;
c) Extension of the graphical approach to explore 3D graph-comparison; and,
d) Test of versatility by exposing the framework to a different type of design challenge.

The New Actuator – A Design Task

The new actuator has been developed guided by an existing engineering design methodology. This has enables assessment of the framework working in conjunction with an overall system design methodology. This will allows development of the framework to better work with system design methodologies, and also facilitates understanding of the points in a system design process where the framework may be of utility.

This thesis examines the validity of the developed framework, not the effectiveness of new actuators. As such, the focus of this chapter is **not** on how effective the actuator is, but on **how effective the component choices are**.

Actuator Development

Applying the selection framework from start to finish of a design task allows results to be gleaned around the efficacy of the framework, and also its effectiveness and usefulness at different *stages* of the design task. This differs from case study 1, as all aspects of the system can be changed rather than trying to retroactively select components and maintain the mechanical design.

Pahl and Beitz's Engineering Design methodology will be utilised throughout, as it is considered to be very well-established, highly regarded, and heavily cited methodology, therefore representing a good example of typically employed methodology.

Application of the framework at a concept-level has proven useful, facilitating assessment of the various components which could be employed. With reference to the CAD model developed, the system is expected to look something like figure 123. To explain operation briefly, Actuator 1 is supposed to turn a turntable (arrowed) at 90° increments enabling Actuator 2 to align with the "holes". Actuator 2 will adjust tension in tensile elements of a hypothetical extrinsically actuated system. The idea behind this actuator is to facilitate control without an individual motor being needed for each tensile element, as is typically the case currently.

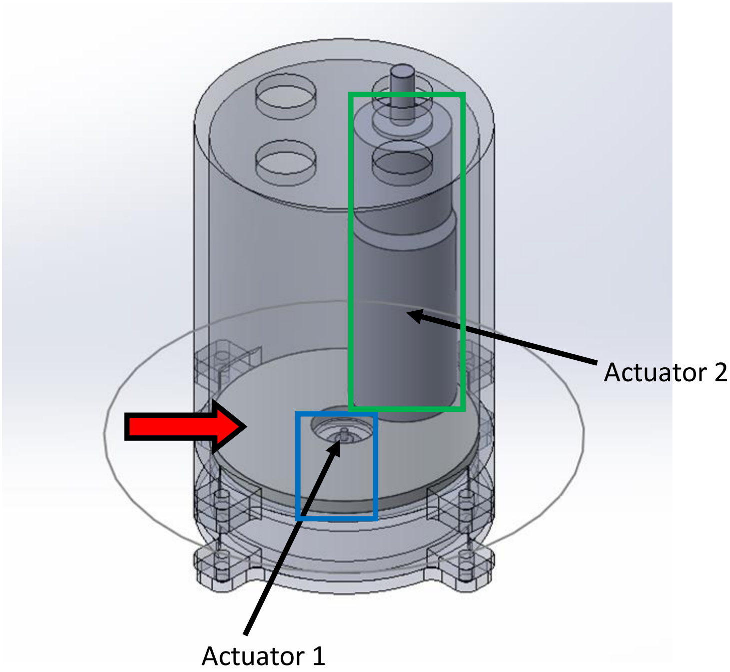


Figure 122: The design of the actuator. The red arrow points to the turntable. The position of actuator 1 and actuator 2 are also highlighted in blue and green boxes, respectively.

C.8. Selection in Case Study 2

C.8.1. Actuator 1 – Bearing Selection

To provide a rapid insight into the process, the findings of AHP are presented along with the main graphs of interest.

Table 66: AHP for bearing in actuator 1

Criteria	Percentage	Order of Precedence
Dynamic Load Rating	35.4%	1
Cost	4.3%	5
Mass	8.3%	4
Static Load Rating	27%	2
Outside Diameter	25%	3

Table 49 demonstrates the utility of AHP in order of precedence definition. From here, guidelines were applied as in previous instances. Eventually, a bearing is selected relative to the most desirable trait from AHP; minimisation of outside diameter. Figure 124 highlights the utility of graphs in guiding selection of the SKF AXK 2542 bearing.

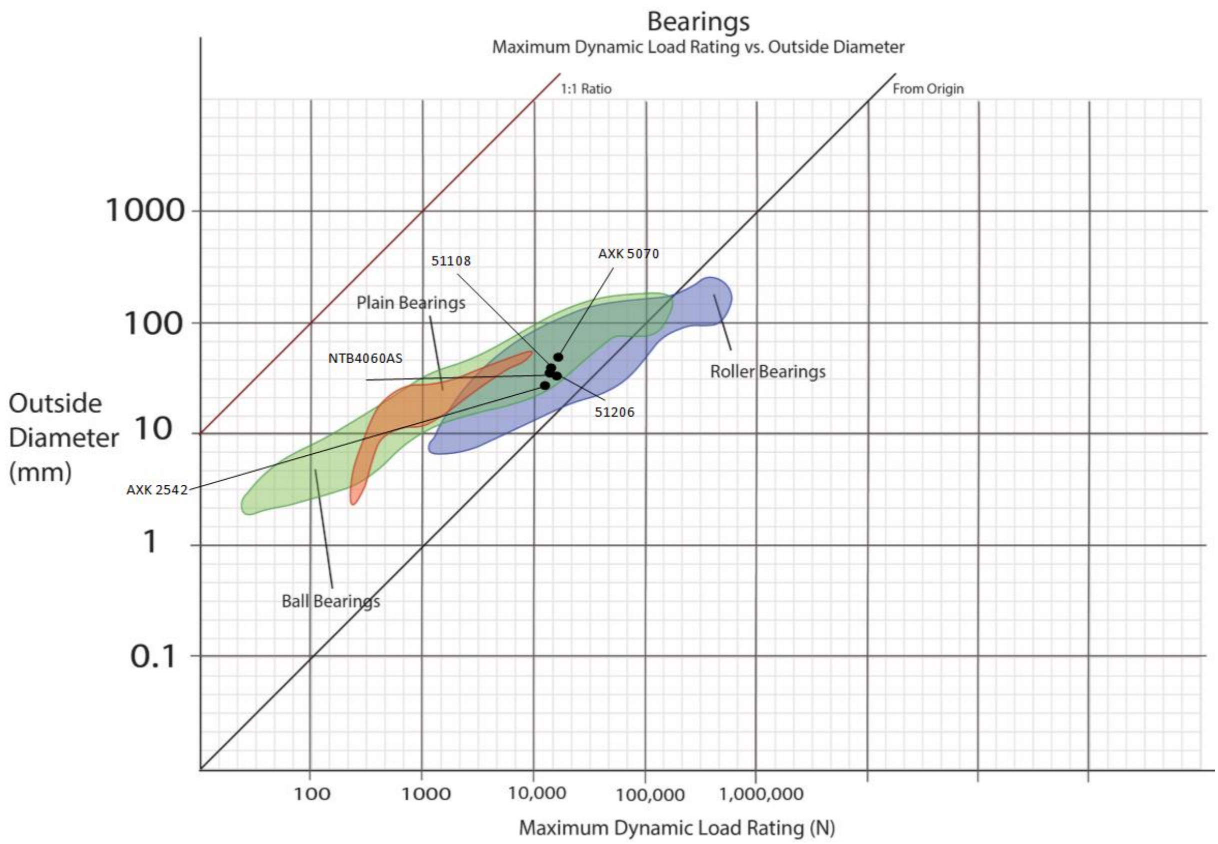


Figure 123: Overview of components considered. Plot shows MDLR against OD.

This demonstrates that the framework is usable for finding solutions to auxiliary functions, and has also facilitated better understanding of the applicability of the framework. Whilst the only auxiliary component facilitated at this time is for bearings, there is no observable reason why this approach cannot be extended to couplings, circlips, bore reducers, and so on.

C.9. Case Study 3

C.9.1. Overview of the application case

As a means to demonstrate the various capabilities of the Advanced Forming Research Centre (AFRC), a demonstrator cell is to be developed, analogous to existing cells; see figure 123. This cell will be developed with scope to expand its capabilities, but in the first instance will robotics, metrology, and machining capabilities of the centre. As it is a prototype demonstrator, it is aimed to develop hardware as **cost-effectively as possible**.

Figure 124: Engaging Robotic Interactive Cell (ERIC)
(https://www.strath.ac.uk/engineering/electronicelectricalengineering/news/ericcelldemonstratestheconceptsbehindstrathclyderesearch/)

Proposed Concept

The proposed idea is to capture inputs through laser scanning to create a 3D point cloud. This 3D point cloud will then be converted into a robot path, allowing a styrene/balsa wood workpiece to be machined to replicate the feature scanned.

Enabling Systems

In order to enable the system proposed, bespoke hardware is required, which will be developed in this chapter.

Hardware

The focus of this case study is a custom tool to facilitate "machining" of the workpiece. A tool to hold a 3D scanner (see figure 124) will be a static system with no motors, etc. required, so will not be developed in this chapter.

Figure 125: Laser scanner to be used to create point cloud.

A point to consider for the machining end effector development: a KUKA KR-90 robot is to be used as the test case. It is a 6-axis system, but the distance between A5's rotation and the robot flange is so large as to present an access problem (see image 1, figure 125); the distance is 298 millimetres, assuming no other apparatus is included (force-torque sensors, etc.). This is too big, so the end effector for material removal will be equipped with a "seventh" axis to enable easier access for the material removal. The material removal end effector will be developed from scratch and will be housed in a 3D-printed assembly.

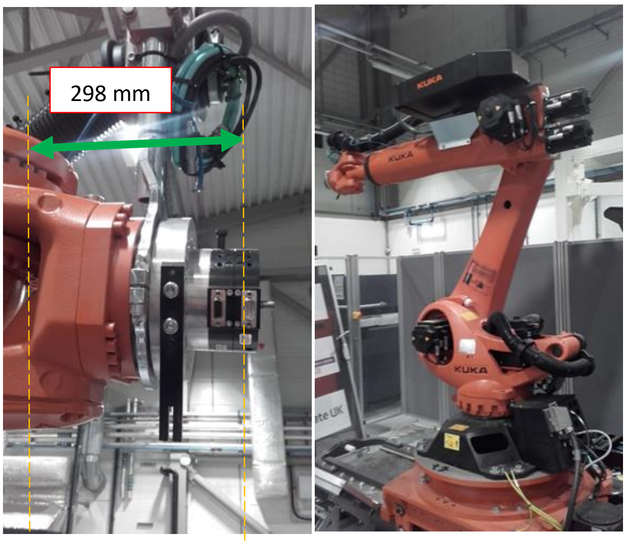


Figure 126: Overview of the robotic system used in this demonstrator test case. Image 1, shown left, illustrates the distance from axis-5 to the mounting flange on the tool-changer for this robot.

Software

There are 3 main pieces of software to be considered in this work:

1. The robot controlling software, in KUKA robotic language (KRL);
2. The laser scanner controlling software, using Polyworks as a platform; and,
3. The software controlling the motors through the motor drivers, which will most likely be enabled through Arduino or Raspberry Pi, in the first instance.

The process flow of communication is outlined in figure 126. There is an eventual need to integrate the software in points 2 and 3 through the robot's PLC in the robot cabinet. From there, the software can be controlled through commands in the robot controller, but this is not a key concern of this thesis.

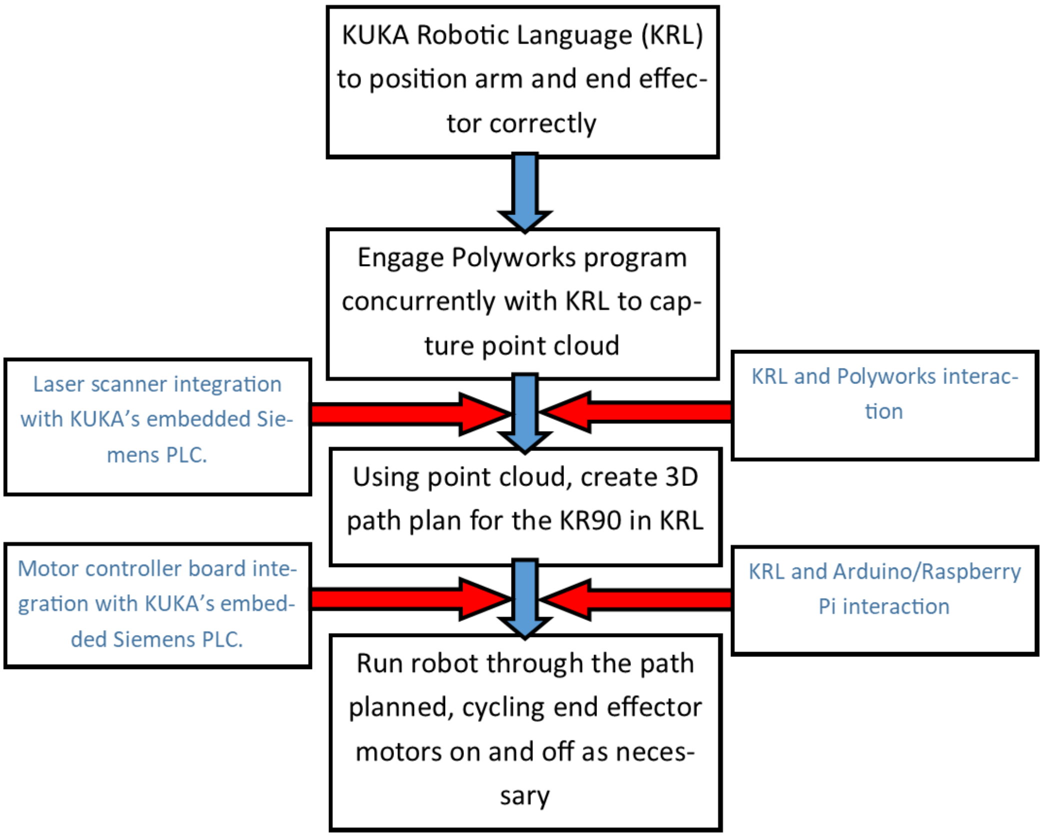


Figure 127: High-level process flow of robot-software integration (RSI) in proposed demonstrator.

C.9.2. System Development

Following development of a system design specification (key elements summarised in table 67), concept level development of the system has been undertaken in line with the framework's guidance. As intimated, whilst providing function is one of the key drivers of this case study's goals.

Table 67: Overview of key points pertaining to design specification for the demonstrator end effector.

Requirement	**Requirement**
Geometry	Must provide an additional axis of rotation to enable a "7^{th}" axis on the robot
Geometry	The tool used for material removal should extend at least 40 mm beyond any supporting apparatus
Geometry	Arrangement of system must allow for a high speed machining element and an assembly to facilitate movement around an additional axis
Kinematics	System must allow movement around an axis parallel to that of A5 of the robot
Kinematics	Range of motion around axis must be 90° either side of the axis extending from the centre of the robot flange
Forces	Actuator enabling the "axis" on the EE must be able to resist the torque applied due to material removal process
Forces	Actuator driving the material removal process must be able to operate with enough torque to remove material without stalling
Energy	No component should require more than 12 volts
Operation	The material removal element must have ample capability to cut through styrene or equivalent
Operation	The system must provide scope through "axis 7" to reach into areas necessary to facilitate 3D scanning
Operation	The material removal element must provide scope to extend far enough away from the rest of the end effector such that the rest of the end effector is no impedance to access of the material removal element
Costs	The demonstrator under development is a proof of concept iteration. As such, the costs should be minimised across all elements of the system so far as possible without adversely affecting lessons which can be learned from the system's performance.
Function	Enable movement of cutting tool around an additional axis.

Mechanical Design

Overview of the mechanical design of the end effector is presented, detailing for the end effector. Selection of components will be dealt with in later sections. The end effector designed is presented in figure 129, below. Actuator 2 is effectively a machining tool, required to provide sufficient torque and speed to enable cutting of a material such as balsa wood or styrene blocks. Actuator 1, meanwhile is required to provide an additional axis of rotation around which the machining actuator is able to be manoeuvred.

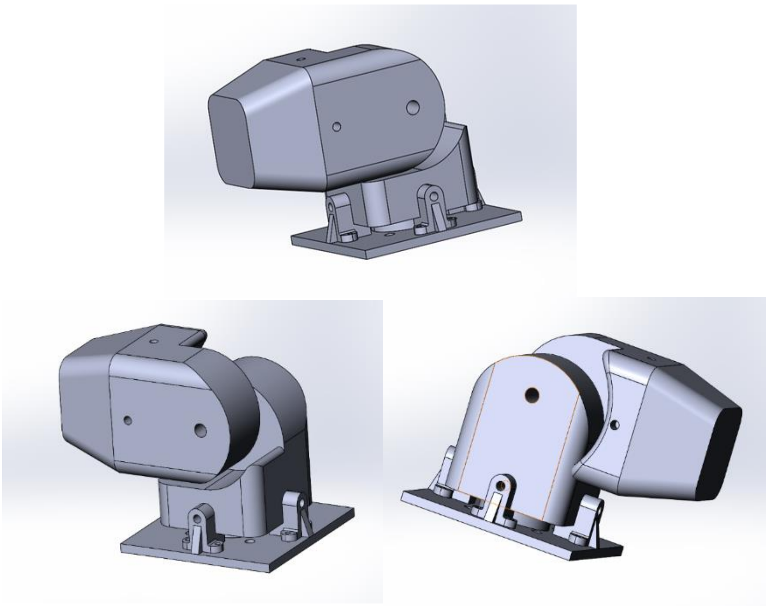


Figure 128: Basic design of the end effector. No components yet selected and the design is yet to be refined.

Framework guidance dictates the need to define key requirements of the system prior to progression to assessing suitable components to meet these requirements. Requirements are documented in tables 68 and 69. Further requirement definition application of the framework at concept-level is available for review in appendix.

Table 68: Key requirements of actuator 2.

Criteria	Value
Power	0.016 kW
Torque	0.044 Nm
Speed	3,500 RPM
Inertia	N/A

Table 69: Requirements from actuator 1's system performance.

Criteria	Value
Power	0.103 W
Inertia	$\mathbf{5.56 \times 10^{-3}\ kg\ m^2}$
Torque	0.588 Nm
Speed	10°/s =
Acceleration	10°/s^2

Full application of earlier stages is documented in appendix E.3., where no further issues with the concept-level guidelines have been encountered. The framework has again evidences utility when used in this way, and the graphs are found to be helpful, but require understanding of the information presented in order to understand how to use each graph. As outlined earlier, this work should not outline how to use *each* graph – a degree of competence from engineers can be assumed. It is though, further demonstrated that for each graph there is a need to use the information from the graphs in a different way – equally, this process should not be constrained in a manner which inhibits effectiveness of users.

C.9.2.1. Concept Solution Summary

Candidate solutions at concept-level are summarised in the below table 70:

Table 70: Summary of components outlined for use for concept-level solution.

Component Type	**Actuator 1**	**Actuator 2**
Motor	BDC, Stepper, or Geared DC	BDC or Geared DC
Transmission	N/A	Worm, spur, or planetary gearbox
Brake	N/A	N/A
Bearing	Ball Bearings	Ball Bearing

Even without *specific* component selection, graphs can be used to inference criteria about component types; i.e. from the information already developed about the components that will be used, the graphs can be used to develop *estimates* about the mass and geometry data of the component types used. Doing so for actuator 2’s mass has enabled estimation of the torque required to manoeuvre this actuator and the joints by actuator 1. This process I covered in greater detail in the appendix E.3.

Appendix D

D.1. Guidance on use of graphs

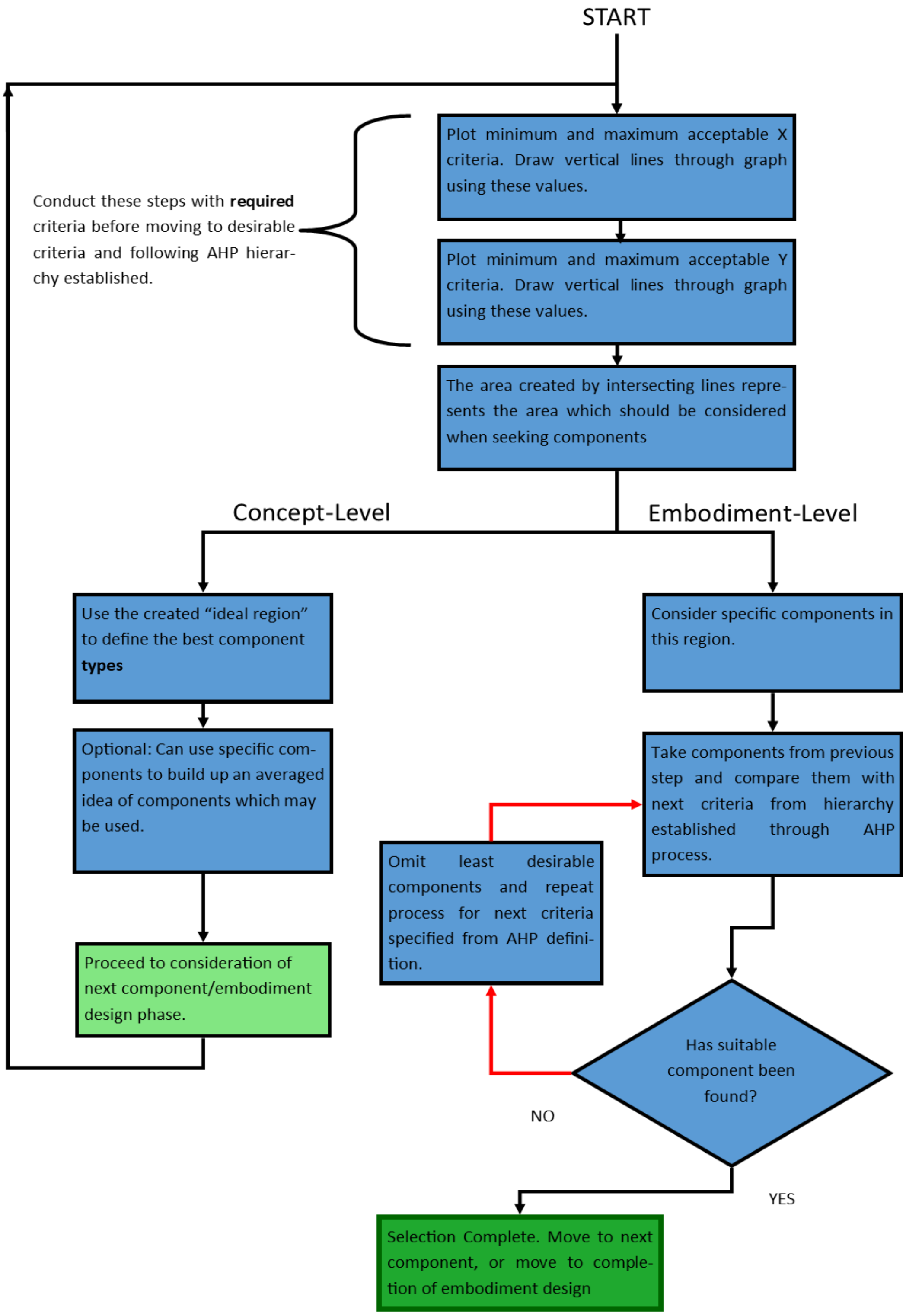


Figure 129: Guidelines for application of graphs in quantitative criteria consideration to support component selection.

Appendix E – Abbreviations and Acronyms

COTS – Commercial off the shelf

IoT – Internet of Things

SCARA – Selective Compliance Assembly Robot Arm

NASA – National Aeronautics and Space Administration

DoF – Degrees of Freedom

EOAT – End of Arm Tooling

I4.0. – Industry 4.0

VR – Virtual Reality

AR – Augmented Reality

A.I. – Artificial Intelligence

pHRI – Physical Human-robot Interaction

HRI – Human-robot Reaction

DC – Direct Current

BDC – Brushed DC Motor

BLDC – Brushless DC Motor

AC – Alternating Current

RPM – Revolutions per Minute

HAM – Hydraulic Artificial Muscle

PAM – Pneumatic Artificial Muscle

TRL – Technology Readiness Level

SMP – Shape Memory Polymer

SMA – Shape Memory Alloy

EM – Electromagnetic

EMR – Electromagneto-Rheological

CVT – Continuously Variable Transmission

RVD – Rotary Vector Drive

UML – Unified Modelling Language

CES – Cambridge Engineering Selector

OM – Oriental Motors

OEM – Original Equipment Manufacturer

ER – Electro-rheological

EMF – Electromagnetic Force

AHP – Analytic Hierarchy Process

ANP – Analytic Network Process

TOPSIS – Technique of Order Preference Similarity to the Ideal Soution

MDL – Modified Direct Logic

FoS – Factor of Safety

CS1 – Case Study 1

CS2 – Case Study 2

CS3 – Case Study 3

MDLR – Maximum Dynamic Load Rating

MSLR – Maximum Static Load Rating

OD – Outside Diameter

ID – Outside Diameter

V-REP – Virtual Robotics Experimental Platform

MBD – Multi-body Dynamics

AFRC – Advanced Forming Research Centre

JED – Journal of Engineering Design

IAC – International Aeronautics Congress