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Analysing approaches to specify automated manufacturing systems

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Copyright Statement

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ANALYSING APPROACHES TO SPECIFY AUTOMATED MANUFACTURING SYSTEMS

by

JONATHAN WALKER

A thesis submitted to the University of Plymouth

in partial fulfilment for the degree of

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Recognition is also due to my family for supporting me in this endeavour. Many weekends of being glued to the laptop with headphones on to aid concentration have finally proved worthwhile in the production of this thesis.

The host company in which the experiments were conducted deserves a large helping of gratitude as well. The patience of the owner, particularly when early results were not forthcoming was very much appreciated. Added to this was the willingness of staff at all levels to engage with the author and answer questions. This also extended to employees of customers and suppliers doing business with the host company who gave their time to take part in discussions around automation.

ii. Author's Declaration

At no time during the registration for the degree of Master of Philosophy has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee. Work submitted for this research degree at the University of Plymouth has not formed part of any other degree either at the University of Plymouth or at another establishment.

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iii. Abstract

Jonathan Walker – Analysing approaches to specify automated manufacturing systems

Automating manufacturing systems can achieve competitive advantage leading to growth in profits through efficiency gains and other advantages including safety of workers and quality of produced products. However, without accurate specification there is no guarantee of realising return on investment. Automated systems are becoming more complex as the need for customisability and variability of products increases and can only be satisfied through flexibility of production processes. To aid companies in specifying automation and mitigate the risks of project failure an approach is needed that guides users choices. The aim of the research was to investigate approaches to specify automated manufacturing systems to provide a basis for a methodology that would aid practitioners in this difficult task.

The objectives were in two phases. Firstly to categorise and criticise conclusions of other researchers resulting in identification of themes and criteria for an approach. Secondly to experiment empirically with promising approaches in a company producing of automated manufacturing systems (AMS) and compare the results of the experiments with those found in literature and provide a ranking of themes and criteria to aid future researchers in designing new approaches to specify AMS. The methodology used was literature review followed by mini case studies in a host company to test theory. The results from literature and the experiments were classified into four themes quantitative modelling and simulation (QM&S), database decision aids (DDA), flowcharts and consultancy. These were compared using analytical hierarchy process (AHP) against the identified criteria; rapid application, usability by managers, considering costs and benefits other than financial ones, reducing required

resources, being applicable to engineer to order products and usable at the early stage of planning.

The results were the strengths and weaknesses of each theme defined by the identified criteria and showed that none of the themes fulfilled all of the criteria for an approach to specify AMS. For this reason a hybrid approach was proposed beginning with a flowchart group session to make an outline plan, followed by a database decision aid to provide options and guidance in creating a detailed plan. Finally, an optional simulation stage could test the planned system for suitability. It is hoped that the comparison of approaches will aid future researchers in the creation of new approaches to assist engineers in specifying automated manufacturing systems in a rapidly changing world.

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vi. List of acronyms

AGV – Automated Guided Vehicle

AHP – Analytical Hierarchy Process

AMS – Automated manufacturing systems

ASML – Automation System Modelling Language

CAD – Computer Aided Design

DDA – Database Decision Aid

ET – Exploratory Testing

ETO – Engineer to Order

IoT – Internet of Things

ISO – International Organisation for Standardisation

QM&S – Quantitative Modelling and Simulation

VR – Virtual Reality

VSM – Value Stream Mapping

1 Introduction

This Introduction Chapter will describe the research context and purpose following the advice of Cresswell (1994) who declared that an introduction should consist of establishment of the problem requiring study, setting the problem within existing literature, discussing the limitations of the literature, describing the intended audience of the research and why it is significant for them. These are covered below with a section on the research context, followed by sections on definition of automation, criteria for design, automation specification process steps and structure of methodologies, and the intended audience. This is followed by the research aims and objectives, the research questions and finally a brief section on the organisation of the thesis.

1.1 Research background

In the last few years, the rate of technological advancement has increased and according to Nikulin (2015), companies need to predict future products and processes of manufacture because those that do not can fail to compete. Recent research by Rauch et al. (2020) found that companies want their manufacturing facility to evolve quickly to adjust to changing product configurations, with easy set up of machinery and that automation can be used to achieve higher efficiency, productivity and adaptability. However, Thomassen et al. (2014) claimed there is rapid development of manufacturing technology, but a high number of implementations fail to achieve their potential benefits.

The need of the design engineer for an approach that provides information on capabilities and costs of manufacturing processes has been recognised for a long time but there is a relatively small amount of research published according to Swift and Booker (2013). Leiber and Reinhart (2021) state that decisions on automation of manufacturing require expert knowledge and manual effort and Goh et al. (2020) tell us that these decisions involve many variables such as return on investment, reliability, competitive advantage, resources and technology availability. Due to the increasing need for flexibility and adaptability of automated manufacturing systems (AMS) to supply the need for customisation, the systems themselves are becoming more complex according to Alkan and Harrison (2019). For these reasons, an approach is needed to assist engineers in specification of AMS. The next section defines automation in the context of this research, followed by a section on the criteria for specification of automation.

1.2 Definition of automation

The Cambridge Dictionary defines automation as “the use of machines that operate automatically” or in business English “the use of machines or computers instead of people to do a job, especially in a factory or office”. It is interesting that the concept of automation replacing people is introduced in the business English definition. This is an example of companies trying to maintain production and reduce costs whereas others may attempt to increase production while retaining their current workforce by redeploying employees to other roles. Several researchers define levels of automation (LoA) ranging from fully manual to fully automated with combinations of manual/automated in between (Salmi (2018), Winroth et al. (2006), Fasth (2011), and Fast-Berglund and Stahre, (2013)). The progression of automation in manufacturing is discussed by Bortolini et al. (2017) when considering assembly system design and they present the information in Table 1. Many businesses have not fully implemented the 3rd industrial revolution so are unable to jump to the 4th.

Table 1: Period, technology innovation and production paradigm of the four industrial revolutions - adapted from Bortolini et al. (2017)

	1st industrial revolution	2nd industrial revolution	3rd industrial revolution	4th industrial revolution
Period	1780-1860	1870-1950	1970-2000	2000 -
Technology innovation	steam power & machine tools	electricity	electronic, IT, automation	Internet connected sensors
Production paradigm	craft production	mass production	mass customization	personalized production

In Nature, Segal (2018) reports that a wide range of estimates exist for the effect of automation on worldwide employment ranging from one billion jobs being created to two billion jobs being lost by 2030. This variability could be due to the multitude of factors involved in the question. However, another approach is to look at how jobs will adapt to automation. Frey and Osborne (2017) predicted in 2013 that 47% of jobs in the USA could be automated by 2030. Three years later an estimate of 9% was suggested, and in 2018, a 14% estimate was given by Nedelkoska and Quintini (2018). These types of changes have happened in the past, for example in the car industry each robot installed resulted in three jobs being lost. If this trend continued, then a four-fold increase in robots would result in a 1% increase in unemployment (1 million jobs lost in the US alone) according to Segal (2018).

1.3 Context of research

For the duration of the research, the author was employed in a “small to medium sized enterprise” (SME) that provides automation solutions. The role was focussed on developing the approach of the business towards the problem of specifying automated production systems faced by both suppliers and consumers of automation and encouraging the use of advanced technology. The job complemented the research by providing practical examples to learn from and an environment to conduct experiments; and the research informed the job by providing useful theories and the accumulated knowledge of the academic community. Through getting involved in the specification process, the needs and difficulties faced by buyers when planning to automate a process were illuminated such as constrained budgets and timelines, lack of expertise, and resistance to change. The provider would seek to overcome these difficulties by setting appropriate pricing, committing to specified lead time, providing free advice, and demonstrating the benefits but this in turn presents a problem for the supplier as these are hard to predict and must be delivered without any guarantee of winning the order and being paid.

The environment and role also provided delimiters for the scope of the research based on the characteristics of the host company and the projects in which they were involved. The company was a small one of only 50 employees so the investigation was mainly aimed at SME providers and smaller scale customers rather than petrochemical plants, and car factories. The machines constructed by the enterprise were bespoke and one of a kind as opposed to systems that are mass-produced and sold 'off the shelf' such as cars and this provided a further boundary. These automated systems were mainly for discrete manufacturing rather than production of fluids or bulk materials, including control, assembly, coating, testing, packaging and labelling. However, the customer base was relatively diverse, serving electronic, medical, food, aeronautical, rail, and nautical companies.

1.4 Criteria for design

When an automated manufacturing system is designed, there are a multitude of criteria it must fulfil to be successful. Some of these relate to the profitability and ability of the supplier but many of these criteria stem from the needs of the consumer of the automated system. These consumers have wants and needs comparable to those felt by consumers of televisions or hamburgers. According to Hill (2000), these criteria can be separated into order qualifiers and order winners. Order qualifiers are the criteria that the machine or the supplying company must meet before being considered in the selection process, for example, ISO 9001 certification, but these do not win orders. Order winners are the criteria that win the order, for example lower cost than competitors or higher perceived quality. In the case of an automated machine, order qualifiers can include achieving the required cycle time or fitting into the specified footprint. Order winners can be concrete such as the cost of the machine and the technology used or intangible like the relationship between the supplier and customer. Further examples of order qualifiers and order winners are gathered in Table 2. Cost estimation is essential when designing and deciding on the LoA of assembly systems according to Salmi et al. (2018b). However, this research focussed on the intangible factors affecting cost, such as the quality and flexibility included by Son (1991) in the cost concept to evaluate performance and justify automated manufacturing system (AMS) implementation to balance up the large amount of existing research in financial aspects that does not necessarily consider performance or acceptance of automation solutions.

Table 2: Non-exhaustive list of criteria for design of automated manufacturing systems divided into order winners and order qualifiers. (Adapted from Hill, (2000) and Lo and Power (2010))

Order Winners and Order Qualifiers in Automated Manufacturing System Design		
Category	Order Winners	Order Qualifiers
Machine	Cost Perceived quality Technology used	Footprint Cycle time Overall Equipment Effectiveness (OEE) Services required (Electrical voltage, compressed air)
Providing company	Relationship between supplier and customer Being an existing supplier	Regulatory compliance (CE, UKCA, BSI, ANSI) Agreeable payment terms Company size Delivery reliability lead time

1.5 Automation specification process steps and structure of existing methodologies

The process of developing automated production systems in manufacturing can vary according to practitioner, company and industry differences but typically follows a logical progression in several stages. The process commonly begins in one of two ways. Either current processes are analysed for opportunities to automate (Lindholm and Johansen, 2018, Sinnwell, Krenkel and Aurich, 2019) or a new product is designed, and the means of production then need to be constructed (Bornschlegl et al. 2015, Salmi et al. 2015). These two starting points require different approaches but the overall process contains many synergies allowing them to be analysed together. Below the similarities and differences identified through taking part in automation planning in the host company are shown in Table 3. This research concerns analysis of approaches to assist with steps two to five and these are the same except for step two.

Table 3: Automation process steps for new product and existing product. (Adapted from the work of Lindholm and Johansen, 2018, Sinnwell, Krenkel and Aurich, 2019, Bornschlegl et al. 2015 and Salmi et al. 2015 and experience of the author the automation projects)

Step	New product/process development	Existing product/process improvement
1.	New product developed	Need identified (e.g. efficiency gain)
2.	Production plan formalised	Current process examined for opportunities
3.	Technology options identified	Technology options identified
4.	Options compared and evaluated	Options compared and evaluated
5.	Chosen solution is designed	Chosen solution is designed
6.	Machine is built	Machine is modified
7.	Solution is tested	Solution is tested

Previous works identified through literature review have also attempted to identify the steps required when planning automation and these are summarised in Table 4. This allows examination of the processes required in chronological order from early to late stages of planning. These stages are further discussed later in the thesis with a particular emphasis on usability of approaches at the early stage of planning. This is arguably the most difficult part of planning for automation as information is sparse and prone to inaccuracy (Salmi et al. 2016) and so the stage that needs more research and presents a gap.

Table 4: Stages of automated manufacturing system planning proposed by other researchers

<table>
<tr><th></th><th colspan="8">Stages of automated manufacturing system planning</th></tr>
<tr><th>Paper</th><th colspan="8">Early → Late</th></tr>
<tr><td>Bhise and Sunnapwar (2019)</td><td colspan="4">Planning and justification phase, considering firstly strategic issues and then technology selection and transfer.</td><td colspan="4">Pre-implementation phase, considering organisational changes, management support, human factors, vendor selection, implementation practice.</td></tr>
<tr><td>Bradford and Childe (2002)</td><td colspan="4">People, structure, technology and process planning</td><td colspan="4">Risk assessment of costs and benefits</td></tr>
<tr><td>Bornschlegl et al. (2015)</td><td colspan="2">Definition of design and available manufacturing techniques</td><td colspan="4">Definition of suppliers and general structure of manufacturing equipment</td><td colspan="2">Definition of PLC programs, cycle time, detailed structure of production equipment</td></tr>
<tr><td>Leng et al. (2021)</td><td colspan="2">Generate idea for system in mind</td><td colspan="4">Form a model through drawing the system</td><td colspan="2">Create physical prototype for testing</td></tr>
<tr><td>Rahman and Mo (2010)</td><td colspan="2">Define user requirements and system constraints</td><td colspan="4">System design process</td><td colspan="2">Design brief</td></tr>
<tr><td>Tan, Otto and Wood (2017)</td><td colspan="2">Conceptual design – data gathering, requirements analysis and functional analysis</td><td colspan="4">Preliminary design – modelling, simulation, process selection</td><td colspan="2">Detailed design – embodiment, requirements validation</td></tr>
<tr><td>Lindholm and Johansen (2018)</td><td>Identify needs and technical feasibility</td><td colspan="2">Justify scope and assess risks</td><td colspan="2">Capture and structure raw knowledge.</td><td colspan="2">Develop product and process models</td><td>Develop application</td></tr>
<tr><td rowspan="2">Sinnwell, Krenkel and Aurich (2019)</td><td>Objectives planning</td><td colspan="2">Preliminary planning</td><td colspan="2">Ideal planning</td><td colspan="2">Real planning</td><td>Detailed planning</td></tr>
<tr><td colspan="8">Each macro planning stage above consists of micro planning stages: Context and requirements planning, technique and material planning, dimensioning and structure planning and technical solution planning.</td></tr>
<tr><td>Salmi et al. (2015)</td><td>Product design</td><td colspan="2">Standardised graphic modelling</td><td colspan="2">Considering criteria and manufacturing preferences, system</td><td colspan="2">Alternative generating</td><td>Cost per product, profitability and performance analysis</td></tr>
<tr><td>Zhang and Agyapong-Kodua (2015)</td><td>Product design, process and implementation planning</td><td colspan="2">Demand analysis</td><td colspan="2">Synthesis</td><td colspan="2">Simulation</td><td>Evaluation</td></tr>
</table>

1.6 Intended Audience

The intended audience of this work are Operations Management researchers in the field of industrial automation and consultants involved in specifying automated production machinery. The comparison of research themes in existing literature with each other and with the results of experiments conducted in a host company will aid future researchers in choosing a methodology. The relative strengths and weaknesses of each theme were identified and these would be useful for those designing a new approach for the specification of automated production systems possibly through blending the best parts of existing methodologies. Consultants may also find some of the developed tools helpful for the difficult task of specifying new or improved production systems.

1.7 Research Aim and Objectives

The aim of the research was to investigate approaches to specify automated manufacturing systems to provide a basis for a methodology that would aid practitioners in this difficult task. The first objective was to review the work of other researchers investigating this topic, through categorising and criticising their conclusions resulting in identification of themes and criteria for an approach. The next goal was to experiment empirically with promising approaches identified in a host company provider of automation of manufacturing to test the themes against the criteria. The third objective was to compare the results of the experiments with those found in literature to provide a ranking of themes and criteria to aid future researchers in designing new approaches to specify AMS.

1.8 Research questions

How can an approach specify automation solutions?

Businesses are constantly striving for greater efficiency, to increase profits (Boothroyd, 2005) and automation is an accepted way of reducing costs of production. The development of modern technologies and industrial growth requires new methodologies for specification of AMS according to Grobelna and Karatkevich (2021). Identifying where and when to automate is mainly driven by cost and a useful metric in making decisions is the cost per product estimated from the number of products produced per unit time and the capital cost of the machinery (Salmi, 2018). However, Goh et al. (2020) tell us there are many other dimensions to the problem of specifying automation both tangible such as the technology used and intangible like the perceived reputational benefit. An approach must guide the user in establishing needs, choosing which process to automate, and deciding on required properties of a new system Leiber and Reinhart (2021). This question is addressed by reviewing the approaches of other researchers and testing some of them experimentally in a host company. Four research themes were identified and used to classify existing work to further aid analysis.

Which criteria are important in an approach to specify automation solutions?

The criteria that are important in an approach to specify automation are different from those described in Section 1.3, which are for the selection of a solution and provider. Criteria for an approach concern its performance for the specification task and include factors such as speed of application (Leng et al. 2021), resource use (Leiber and Reinhart 2021), and ease of use (Busogi et al. 2017) as will be examined in Section 2.4 Criteria for selecting an approach. These were distilled through examining the priorities of previous researchers and their relative importance estimated.

How well does existing literature meet the identified criteria?

Once the criteria for an approach were identified, they were used to assess qualitatively the existing approaches developed by other researchers. This was done through analysis of literature along with the results of empirical experiments in a host company that specialised in automated production systems. Literature themes were compared with each other and the results of the experiments using the identified criteria in an analytical hierarchy process (AHP) created by Saaty, (2008).

1.9 Organisation of the thesis

The thesis is organised into Chapters, Sections and Sub-sections based on a simple numbering system where the first number is the Chapter, second the Section, third the Sub-section and so on. This Introduction Chapter is followed by the Literature Review Chapter, which includes an explanation of the review methodology. Chapter 3 is Methodology and explains the authors' philosophical choices along with the experimental methods used. Chapter 4 details the results of the various experiments conducted and these are subsequently discussed and compared with existing research in Chapter 5. Conclusions are summarised in Chapter 6 followed by a full list of references consulted, then appendices that comprise publications, surveys used along with results, a table of all reviewed literature coded by theme and further details of the experiments.

2. Literature Review

2.1 Introduction

This Chapter assesses and criticises the existing literature reviewed during the research project. A short appraisal of the research background covering the research context and environment is provided at the beginning. This is followed by an explanation of the literature review methodology including planning and conducting the review. The review itself is divided into two major sections: the criteria discovered for an approach and the themes found within the literature. These are further sub-divided into sections for each criteria and theme.

2.2 Research Background

There are several motivations to automate manufacturing and the UK government has been investing in automation and robotics recently to compete in a rapidly changing world. Implementation of automation will become even more attractive to companies to mitigate some of the effects of Covid-19 by replacing vulnerable human workers with automation (Acioli, Scavarda and Reis 2021 and Hitoshi 2021). There is also an increase in the rate of technological advancement and Benešová & Tupa (2017) asserted that to remain competitive businesses will have to adapt. However, according to Ahuett-Garza & Kurfess (2018) there is not enough automation knowledge and experience in industry, leading to a bottleneck for specifying automated manufacturing systems. It is this bottleneck that the author attempted to widen by investigating approaches to make the specification of automation faster, easier and more holistic.

Literature reviews by authors with aims that are aligned with this research include the investigation of flexible manufacturing system (FMS) modelling conducted by Yadav and

Jayswal (2018) analysing the benefits and limitations to help researchers decide which modelling techniques to apply to their problem. They concluded that mathematical modelling techniques were most widely used but suffered from assumptions that may not be valid in the real world. Another literature review by Alfnes et al. (2016) examined the usefulness of justification techniques and developed criteria for evaluating them by testing on a development project. They defined good support as being applicable and well explained, easy to follow (low expertise needed), and reducing time and workload required. These are criteria for an approach to specification of automation, which led the author to further investigate and expand below. More recently, Rauch et al. (2020) found through reviewing literature and searching Scopus that there is still a lack of research detailing the requirements and difficulties of implementing automation to manufacturing.

2.3 Literature review methodology

2.3.1 Planning the review

The author began by having conversations with manufacturing industry managers about the problems they faced when specifying and designing automated manufacturing systems (Table 5). These included lack of time, experience, money and the consideration of non-financial costs and benefits. An approach was needed to assist managers with the many decisions required. From this need the three research questions in

1.8 Research questions were developed. To investigate relevant literature these were refined into the search words: "manufacturing, design, specification, automation, automated, system, implementation, modelling and production". Due to accessibility, the main database used was the Plymouth University Electronic Library ("Primo"), augmented with searches on google scholar. Inclusion criteria for the initial group of papers were "does the paper address automated manufacturing?" and "is there a methodology for specification?". Exclusion criteria were "is the paper in intelligible English?" and "is the paper from a respected journal?". As the study progressed, further exclusion criteria were developed such as excluding papers that prioritised optimisation or only concerned the control system of the automated production, as these did not fully address the problem.

Table 5: Managers and Engineers consulted on the problems they faced when specifying and designing automated manufacturing systems.

Title	Field	Expertise	Number
Managing Director	Bespoke Machinery Manufacturing	Control Systems, Automation	1
Production Manager	Bespoke Machinery Manufacturing	Electrical design, Pneumatics	1
Mechanical Engineering Manager	Bespoke Machinery Manufacturing	Mechanical design, Tooling, Robotics,	1
Control Systems Engineering Manager	Bespoke Machinery Manufacturing	Control System Design, Software Design, Commissioning Machinery	1
Manufacturing Engineering Manager	Electronics Manufacturing	Electronic Engineering, Quality Management, Production Management	1
Continuous Improvement Manager	Plastics Manufacturing	Production Optimisation, Health and Safety, Automation	1
Control Systems Engineer	Bespoke Machinery Manufacturing, Electronics Manufacturing	Software Design, Hardware Specification, Electronic Engineering, Test System Design	4
Project Engineer	Bespoke Machinery Manufacturing, Electronics Manufacturing, Plastics Manufacturing, Medical Product Manufacturing.	Continuous Improvement, Six Sigma, Project Management,	9

2.3.2 Conducting the review

The first step recommended by Tranfield, Denyer and Smart (2003) is to identify keywords and terms to search with using a scoping study and the literature. Then decide on the most relevant search strings, and record the process so that it can be replicated. The combinations of the search words identified in the previous section resulted in the search strings in Table 6 that were entered as presented. The researcher must review all relevant citations and conduct detailed evaluation to include or exclude them based on a checklist of criteria, whilst recording their reasons for doing so. The author used a spreadsheet to assist with this which when converted to a table provided the benefit of being able to order the rows alphabetically or in ascending numerical order using the column headings. The quality of a study must be assessed on the quality of its methodology as well as the relevance of the research questions according to Cook, Mulrow and Haynes (1997). Some factors for assessing qualitative research are shown in Table 7.

Table 6: Search strings as used in literature search

Search strings
manufacturing system design, manufacturing specification, manufacturing automation, automation specification, modelling manufacturing, automation modelling, automation system modelling, specification of automated manufacturing, automated manufacturing design, automated manufacturing specification modelling,

Table 7: Factors to assess quality of literature review adapted from Cook, Mulrow and Haynes (1997)

Factors	Questions
Sampling strategy	Selection shaped by theory?
Context sensitive	Flexible to changes?
Data quality	Different sources compared or explored?
Theoretical adequacy	Is data to interpretation process explicit?
Generalisability	Logical?

The quality of the study can be inferred from the quality of the journal in which it is published according to Tranfield, Denyer and Smart (2003). This was done using the Scimago journal rankings accessed at https://www.scimagojr.com/journalrank.php and recorded on the review spreadsheet. No studies were excluded based on journal impact factor but those from journals with scores higher than three were considered to be from more reliable sources and were given greater precedence. The literature-reviewing tool Mendeley was also used to store and review the papers, which gave the benefits of being able to highlight relevant phrases, take notes and search the collected body of work with keywords.

The search terms resulted in thousands of results, many of which were only marginally relevant to this research. These were narrowed down by refining the search terms further and including more of them in the search string. This resulted in finding a number of excellent examples that attempted to solve similar problems about automation specification but in a multitude of different ways. The references of these papers were then scrutinised for further leads and this led to the discovery of many more papers on the specific topic at hand amounting to 220 in total. The content of these papers led to the discovery of several common criteria for an approach to specify automation. These were then used to search the collected body of work in the Mendeley referencing tool to discover other works supporting that idea. This formed the basis of 2.4 Criteria for selecting an approach. Coding of all papers was done using an excel spreadsheet and this revealed the four themes and various sub-themes related in Section 3 “Research themes”.

2.4 Criteria for selecting an approach

2.4.1 Introduction

When reviewing papers that developed similar ideas about assisting companies to implement automation the author noted some of them described criteria they identified as important. These were mentioned explicitly in a sub-group of 27 papers within the overall total of 220, mainly in the introductions, conclusions or future work sections. The author has attempted to gather the important criteria, from other authors work (Table 8), to define the objectives of an approach to aid in implementation of automation. Those criteria that are mentioned in many papers are accepted to be important to include but are already researched intensively. However, those that are only mentioned in a smaller number of papers can still be considered important as they have been identified, and they provide more opportunity to develop new knowledge. There are several caveats to ranking criteria based on the number of papers that can introduce error. The number of papers may be influenced by those issues that are easy to research, or easy to measure. The authors' area of expertise will also affect the subjects they consider important for example management scholars focussing on workplace issues.

Another factor affecting the viability of an approach is the methodology that led to it. Those that rely purely on theory from literature or experiments in laboratories are less likely to be accepted and used in industry. Conversely, those that are developed in the industrial environment and through collaboration with industry are seen to provide face validity. This face validity makes it more probable that these approaches will be adopted in the real world resulting in further verification of their usefulness. They are adopted during the course of the research and if they are useful, they will continue to be used providing verification of the approach.

Table 8: Approach criteria identified from literature (O – criteria mentioned, X – solution proposed).

Author \ Specification Criteria	Rapid application	Useable by managers with technical knowledge	Consider not just financial costs and benefits	For small businesses/resource use	For ETO products	Useable at the early stage of planning
Alfnes et al. (2016)	O	X	X			
Baines (2014)		X				
Bornschlegl et al. (2015)						X
Bradford (2000)	O	X		X		
Busogi et al. (2017)	X					
Chan et al. (2001)			X			
Chen and Small (1996)			X			
Farooq and Obrien (2012), (2015)		X	X			
Guschinskaya et al. (2011)	X	X				
Hamzeh et al. (2018)		X	X	X		
Heilala, Helin and Montonen (2006)	X					X
Lindström and Winroth (2010)		X	X			
Michalos, Makris and Mourtzis (2012)	X	X				
Ordoobadi and Mulvaney (2001)	X		X	X		
Rahman and Mo (2010), (2012)	X	X				
Ramis et al. (2015)						X
Roy et al. (2017)			X			X
Salmi et al. (2015), (2018)	X		X			X
Salmi et al. (2016)						X
Sambasivarao and Deshmukh (1995)			X			
Sambasivarao and Deshmukh (1997)	X	X	X			
Savoretti et al. (2017)	X	X			X	X
Shehabuddeen, Probert and Phaal (2006)	X		X			
Thomas, Barton and John (2008)		X		X		
Thomassen, Sjøbakk and Alfnes (2014)	X	X	X		X	
Zennaro et al. (2019)				O	O	

2.4.2 Rapid application

Rapid application was explicitly mentioned by 13 authors (Table 8) and many proposed ideas to achieve it. Several proposed the use of a software tool to speed up the process of automation implementation. These include a computerised decision support system from Sambasivarao and Deshmukh (1997) however, DSS have been criticised as having low practical relevance by Arnott and Pervan (2005). A similar method to separate 'must have' from 'nice to have' features and use them as filters was developed by Shehabuddeen, Probert and Phaal (2006). Heilala, Helin and Montonen (2006) proposed tools that integrate different methods, and a knowledge database of past cases searched using a case based reasoning system was used by Savoretti et al. (2017). Michalos, Makris and Mourtzis (2012) proposed changing the problem from a decision to a search, by systematically generating the solution space to include the many design alternatives and implementing in a software tool to evaluate options quickly. A software tool, possibly as simple as a spreadsheet can be used to leverage the speed of computer calculations. Ordoobadi and Mulvaney (2001) attempted a fuzzy expert system based on the results of surveys, which was tested in an industrial setting with promising results. Mapping the complexity of the process was suggested by Busogi et al. (2017), and some form of process mapping was common in many papers. Guschinskaya et al. (2011) used meta-heuristics rather than exact methods because of their 'combinatorial complexity', specifically GRASP (greedy randomised adaptive search procedure). They tested their algorithm on datasets from previous research and found they were significantly faster at solving the problem. However, the problem consisted only of optimally assigning tasks to machining tools and so may not be applicable to general specification of automated manufacturing. A strategic approach with rapid prioritisation was proposed by Thomassen, Sjøbakk and Alfnes (2014), which involved calculating the current and future person-hours for the process. However, depending on the number and complexity of processes this could be a time consuming process.

2.4.3 Usable by managers with technical knowledge

To make an approach usable not just by 'automation experts' makes it more accessible and easier to use and several authors, when writing about implementation of automation, mention this aim. Alfnes et al. (2016) proposed making their method effective, applicable and well explained, which was an idea also found to be important by Lindström and Winroth (2010). Specific and comprehensive guidance was provided by Baines (2004) and it seems evident that providing simple instructions with an approach is important to aid use and make it accessible to a wider audience. Other methods to aid usability were providing people, process, technology and organisation choices during the planning phase (Bradford 2000). This structured the discussion to assist practitioners with decision-making, but their method required a change team bringing together different specialisations. This brings the advantage of multiplying the knowledge available but increases the resources required to make the decisions.

Incorporating the supply chain with manufacturing in an analytical decision making framework was proposed by Farooq and O'Brien (2012 and 2015) and Hamzeh et al. (2018) who wanted to include other business partners as well. Including other stakeholders outside the immediate process of interest could make the process more complicated; however, the knowledge of others would be a benefit. Guschinskaya et al. (2011) claimed that meta-heuristics make their method easier to use, but the data processing is complex and as mentioned above only applied to allocation of tasks. Systematically generating the solution space was advocated by Michalos, Makris and Mourtzis (2012), to reduce the expertise required to specify the automated production line but their method is in itself complex; although they were attempting to apply it to a car production factory so complexity was inherent due to the many parts to assemble and the huge customisability of each car produced including engine, trim, colour, and interior options.

Automatic capture of user requirements was attempted by Rahman and Mo (2010 and 2012a) followed by conversion to a system specification using a database of automation solutions. This is a promising approach, but the development of the database is a huge project in itself. Thomas, Barton and John (2008) claimed that their method was easy to use and evaluated this by giving it to companies to test without assistance. They found that it overcame the problem identified in their survey, of companies not being confident they have the knowledge to implement automation. A strategic approach set out in five steps was suggested by Thomassen, Sjøbakk and Alfnes (2014), which they claimed was self-explanatory and validated with feedback from case company employees. Sambasivarao and Deshmukh (1997) claimed that their computerised DSS made the process easier through a modular approach to aid flexibility. One problem with databases in the automation field is that they quickly become obsolete through continual advances in technology. Finally Savoretti et al. (2017) supported user choices of pre-defined blocks and dependencies at each step. This seems a valid method to increase usability but in the real world, the bespoke nature of automated production systems makes the development of generalisable modules difficult.

2.4.4 Consider not just the financial costs and benefits

The importance of considering other costs and benefits beyond the tangible financial ones was discussed by Chen and Small (1996) and Hamzeh et al. (2018). The inclusion of these factors can help in justifying automation projects that have a high initial capital investment and do not pay for themselves in the desired ROI period (Chan et al. 2001). Several authors proposed ways of incorporating intangibles into their approaches but by nature, they are difficult to quantify. Alfnes et al. (2016) and Chan et al. (2001) suggested a strategic approach that combines economics with factors such as early entry to market and perceived technological leadership. These intangible benefits were also included by Shehabuddeen, Probert and Phaal (2006), who cautioned however, that they are subject to user perception.

Including the benefits to worker safety along with other intangibles was proposed by Lindström and Winroth (2010) and Thomassen, Sjøbakk and Alfnes (2014). For some companies this may be a ‘nice to have’ factor but for those with hazardous environments such as the nuclear power industry this is a major factor. Safety improvements could be quantified over time using data from insurance claims for example. Sambasivarao and Deshmukh (1997) suggested use of multi-attribute decision making approaches to consider intangibles such as risk by calculating three values (optimistic, pessimistic and most likely). This would result in a useful predicted range but uncertainties could cause this to be very large. Ordoobadi and Mulvaney (2001) used a database of past cases to give some economic value to the intangibles. Unfortunately, this relies on the availability of relevant data, which often does not exist. Risk calculations, threats of alternative technology and inter-organisational factors were incorporated by Farooq and O’Brien (2012 and 2015) into their approach to tackle the problem of intangibles. More conventional approaches to justifying the investment are to calculate the final product cost (Roy et al. 2011), or compare the man/machine hours for the process and select labour intensive ones (Thomassen, Alfnes and Gran 2015). Without considering intangible cost and benefits though, these may ignore important cost factors.

2.4.5 For small businesses/resource use

An approach to specify automation could target small businesses by addressing the specific problems they face. Unfortunately, the available approaches used by large businesses are often not applicable to small ones, as it is not possible to reduce their scale (Hamzeh et al. 2019). Small businesses are more prone to uncertainty according to Zennaro et al. (2019) which could be mitigated through planning assistance. However, the main problem faced by small businesses is that of resource poverty according to Bradford (2000), Ordoobadi and Mulvaney (2001), Thomas, Barton and John (2008), and Kaartinen, Pieska and Vahsoyrinki (2017). Bradford and Childe (2002) tell us the result is that small businesses are reluctant to commit those limited resources. They recommend overcoming this using analysis of risks and costs against benefits to confirm the change is beneficial. This resource poverty can be lack of knowledge, expertise and time as well as financial considerations. Ordoobadi and Mulvaney (2001) argued that most justification methods require high levels of each of these. They attempted to overcome this by considering system wide benefits in advanced manufacturing technology (AMT) investment decisions using an expert knowledge base and the users own perceptions of value. Thomas, Barton and John (2008) conducted a survey of 300 businesses, which concluded that many would like methodological help for specifying AMT and developed a strategic consultation approach. This was evaluated on the resource use of time and delivery cost of projects at three case study companies and found to perform better than a control group.

Reviewed papers proposed different solutions to the problem of resource poverty among SMEs. Ordoobadi and Mulvaney (2001) created a tool that incorporates examples of past successes and failures and Thomas, Barton and John (2008) found through a survey that companies felt they did not have the required knowledge to successfully implement AMT and proposed a technology implementation approach to assist them. Kaartinen, Pieska and Vahsoyrinki (2017) suggested Universities could help SMEs with introducing technology and provided their developed digitalisation toolbox free of charge. Authors make their methods applicable to SMEs in several ways such as Bradford (2000) who specifically aimed his method at SMEs by considering perspectives of structure, people, process and technology. Rahardjo and Yahya (2010) found the critical success factors of implementing AMT such as leadership and financial availability through a survey of SMEs. Validation was done by Fasth, Stahre and Dencker (2008) who tested their method in SMEs, and Fulton and Hon (2010) who applied their process for AMT implementation to 73 SMEs. As “for small businesses” is a very broad category, this criterion will focus on resource use. This is arguably the primary factor among the pressures encountered by small businesses and allows the criteria to be more precise.

2.4.6 For engineer to order (ETO) products

The automated systems produced by the authors host company are engineer to order products, as are many large automated systems that a company might introduce. The products produced by the machine are not generally ETO as the level of variation and complexity is too high to be produced or specified automatically. However, as technology advances the possibility of automating “batch size of one” becomes more and more realistic. The uncertainty and variability involved in producing bespoke machine solutions using an engineer to order (ETO) process causes management and planning processes to be excessively complex (Rahim and Baksh, 2003). The approach to specify this type of massively flexible production system may need to be different from one that would specify a machine to produce high volume, low variety products. Normally processes and technology must be adapted from those designed for businesses that produce repetitive products (Hicks and Braiden, 2000). Their work however focuses on production planning and control (PPC) rather than specifying and costing new projects. The flexible system actually has a reduced number of options to choose between, as many “hard” automation solutions are not suitable. Hard automation can be more difficult to specify as it relies more on bespoke tooling whereas flexible automation relies on more modular components such as robots and automated guided vehicles (AGVs).

There is a difference here between specifying a machine to produce ETO products and considering the machine itself as the ETO product. This research concerns specifying the automated system, which will usually be an ETO product. Other research concerning ETO products, which are not automated production systems, can still yield some useful insights such as the work of Thomassen, Alfnes and Gran (2015) who suggested the use of VSM and lean adapted specifically for improvement of the ETO production process. They highlighted the importance of the “customer order decoupling point”, which in the ETO case is when the product is specified and design commences as it prevents costly changes later in production. Savoretti et al. (2017) reviewed the problems with cost estimation of ETO products including subjectivity and knowledge of the cost estimator. They recommended a system to store knowledge of product design and manufacturing to enable faster specification of the product and costs. The uncertainty of processing times and planning difficulty were emphasised by Zennaro et al. (2019) as production planning and control issues associated with ETO products. Nonetheless, no papers found in this research took the perspective that the automated systems themselves were ETO products.

2.4.7 Usable at the early stage of planning

In the context of this research, the early stage of planning is the segment in the specification of an automated production system between deciding to automate something and design manifestation. This is when choices are made on which process to choose and how to automate it. Decisions made at the early stage of planning are very important as changes made later in the implementation are much more difficult and costly. An attempt to measure this by Tan, Otto and Wood (2017), considering the impact of wrong design decisions, found that early decisions accounted for 86% of the cost. Regrettably, at the early stage of planning for automation, there is a lack of data available (Salmi et al. 2015, 2016, and 2018). They proposed overcoming this by considering the product design and the series of micro tasks required to assemble it, then calculating times to give cost benefits. They did this by combining equations from different cost calculation techniques, which needed a database of actions and times that unfortunately does not exist. Michalos, Makris and Mourtzis (2012) also tried to aid decision-making at the early stage and highlighted the difficulty of choosing between many alternatives with limited information. They supported this with five criteria; cost, availability, reutilisation, flexibility and production volume. As these are often contradictory, a matrix was used to normalise the values so that the 'best' option could be selected. To cope with the huge number of alternatives they developed an intelligent search algorithm to derive designs for assembly lines and assess them. While this seems a useful method, it was only verified with one industrial case study and it could only create and choose alternatives based on a skeleton design. This also required expertise to input to the algorithm the actions required, tools and stations that can be used and their number.

Early planning stage decisions were addressed by Heilala, Helin and Montonen (2006) who calculated total cost of ownership using an excel spreadsheet for data entry and a simulation for presenting results. However, this was only for modular final assembly systems that did not require much design. Bornschlegl et al. (2015) also tried to compare alternatives by calculating total costs of running the proposed machinery at an early stage, focussing on energy use using elementary energy units and "Methods-Time Measurement". This suffered from the common problem of acquiring data to input into the calculations and they suggested empirical measurement of power use to build up a database. A software design approach using ontology web languages (OWL) was applied by Ramis et al. (2015) to the problem using design for X – assembly, cost, manufacture, environment, fabrication, etc. They tested their method on a small laboratory cell and found that it helped guide the design but suggested further work on a larger scale to confirm their findings. As with many other methods, they rely on creating a library of components and processes, a task that is problematic due to the huge number of options. Finally Savoretti et al. (2017) used an industrial survey to assess requirements for early estimation of costs, targeting companies that produce ETO products. While these were not producing automated production machines, similar processes and complexity are involved. They proposed using past experience to create a database of knowledge integrated into the CAD software used for design. One issue was that the accumulation of that experience and keeping it up to date would take considerable resources.

2.4.8 Criteria analysis

The literature review revealed six criteria that were important and demarcated the boundaries of this research. These manifestly graduate from broad to specific (Figure 1), where two are general and could be applicable to many management approaches; namely *rapid application* and *usable with by managers with minimal training*. Two are more specific to the specification of automated manufacturing systems; *consider not just the financial costs and benefits*, and *engineer to order products*. The remaining two are particular to the research environment and the part of the specification process, *'for small businesses/resource use'*, and *'applicable at the early stage of planning'*. However, the spectrum does not denote the relative importance of the criteria, which is necessary to compare the themes using analytical hierarchy process.

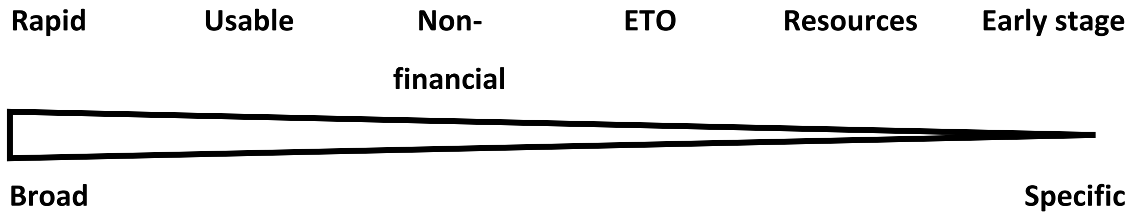


Figure 1: Criteria for an approach on a spectrum of broad to specific

The papers presented in Table 8 are replicated here coded by theme using colours to aid analysis in Table 9. Some papers do not fit into any theme and are left white and Hamzeh et al. (2018) bridges consultancy and DDA, requiring blue and yellow stripes. Although this is a much-abridged snapshot of the literature, selected because the authors explicitly mention one or more of the criteria, the relative proportions for each theme seem reasonably representative of the larger population.

Table 9: Criteria from literature coded by theme.

Author \ *Specification Criteria*	*Rapid application*	*Useable by managers with technical knowledge*	*Consider not just financial costs and benefits*	*For small business/Resource use*	*For ETO products*	*Useable at the early stage of planning*
Alfnes et al. (2016)	*O*	*X*	*X*			
Baines (2014)		*X*				
Bornschlegl et al. (2015)						*X*
Bradford (2000)	*O*	*X*		*X*		
Busogi et al. (2017)	*X*					
Chan et al. (2001)			*X*			
Small and Chen (1997)			*X*			
Farooq and Obrien (2012), (2015)		*X*	*X*			
Ferrer et al. (2015)						*X*
Guschinskaya et al. (2011)	*X*					
Hamzeh et al. (2018)		*X*	*X*	*X*		
Heilala et al. (2006)	*X*					*X*
Lindstrom and Winroth (2010)		*X*	*X*			
Ordoobadi and Mulvaney (2001)	*X*		*X*	*X*		
Rahman and Mo (2010), (2012)	*X*	*X*				
Roy et al. (2011)			*X*			*X*
Salmi et al. (2015), (2018)	*X*		*X*			*X*
Salmi et al. (2016)						*X*
Sambasivarao and Deshmukh (1995)			*X*			
Sambasivarao and Deshmukh (1997)	*X*	*X*	*X*			
Savoretti et al. (2017)	*X*	*X*			*X*	*X*
Shehabuddeen et al. (2006)	*X*		*X*			
Thomas, Barton and John (2008)		*X*		*X*		
Thomassen et al. (2014)	*X*	*X*	*X*		*X*	
Zennaro et al. (2019)				*O*	*O*	
Total	*13*	*13*	*13*	*5*	*3*	*8*

Quantitative modelling and simulation	**Database decision aids**	**Flowchart modelling**	**Consultancy**

2.4.9 Summary

The above criteria have helped to shape the boundaries of the problem of specifying automated production lines. Researchers have attempted to meet the criteria using a range of solutions with varying levels of success, from solving the problem and verifying efficacy through several case studies to merely proposing a part solution based on literature. Another factor is that some of the criteria, for example rapid application and considering not just the financial costs and benefits, while not contradictory are competing for priority and resources. The relative importance of the criteria is difficult to assess except through the crude method of counting the numbers of authors supporting them in Table 8. Important caveats to this method are related in Section 2.4.1 Introduction.

2.5 Research Themes

2.5.1 Introduction

During review of literature, four distinct research themes emerged, which were used to categorise the papers. Although the themes represent different approaches to the problem, several of the reviewed papers included elements from more than one theme. Of the 220 papers selected through systematic literature review on specification of automated manufacturing, a majority of 149 fitted into one or more of the themes. Of the others, many were reviews of specific technologies such as virtual reality (VR) or Internet of things (IoT), or of the possibilities of Industry 4.0, but provided background insights into the research questions.

The first to be identified and most common theme was Quantitative modelling and simulation (QM&S), which involves turning gathered data into information to aid decisions through input to mathematical models often created on computers. This can be used in an approach for specifying automation by mathematically modelling current or proposed processes to aid in cost-benefit calculations and ultimately the decisions required. The second theme was database decision aids (DDAs), which attempt to use data on previous cases to guide the user in decisions on future projects. These DDAs can recycle knowledge to make the specification task possible for those with less experience. This was the least used theme identified, which could lead the author to infer that this direction is less promising. Conversely, the relative lack of current research could present an opportunity for original research. The third identified theme was flowchart modelling, where qualitative diagrams are created to assist in planning of new systems. Some authors used flowcharts to illustrate the steps of their approaches, while others applied them as part of the approach to map the existing or proposed manufacturing systems. Finally, a consultancy/tools for cost and time calculation theme was developed, which involves interviews, meetings and expert analysis and advice. These themes are described and criticised in detail in the following sections. The average journal impact factor of the reviewed papers was analysed and no significant difference was found between the themes (Table 10).

Table 10: Mean impact factors of each theme.

	Mean Journal Impact Factor	Standard Deviation
QM&S	3.58	2.26
DDA	3.81	2.22
Flowchart	3.81	2.91
Consultation	3.02	2.04

2.5.2 Quantitative Modelling and Simulation

Quantitative modelling and simulation (QM&S) was used to assist with implementation of automation by the authors of 76 of the reviewed papers. This theme includes diverse methods with various levels of complexity, from the Excel spreadsheet and visual simulation by Heilala, Helin and Montonen (2006) to the Assembly Sequence Modelling Language and database of action times developed by Salmi et al. (2016). A review of this group of methods was conducted by Yadav and Jayswal (2018) which lends weight to this being a distinct theme in specifying automation. There follows an evaluation of the strengths and weaknesses of this theme against the six identified criteria.

QM&S was claimed to be rapid in application by Bradford (2000), Heilala, Helin and Montonen (2006), Shehabuddeen et al. (2006), Guschinskaya et al. (2011), Busogi et al. (2017), and Salmi et al. (2018), Oppelt, Wolf and Urbas (2015) by decreasing the time required to test alternatives. However, QM&S could involve long computer processing times (Salmi et al. 2018), and be time consuming to set up and adapt according to Fischer, Obst and Lee (2017).

Usability by managers with technical knowledge of QM&S through a simple graphical user interface was claimed by Rahman and Mo (2012b), and ease of use by Bertolini, Esposito and Romagnoli (2020). Overwhelmingly though many other authors found QM&S required knowledge and experience (Ng, Urenda and Svensson 2007) and acquisition of data was difficult (Wuest et al. 2016 and Lechevalier et al. 2018). Additionally, a lot of work was needed to set up a QM&S (Fischer, Obst and Lee 2017), Petri nets could become unmanageably large (Kim and Lee 2013 and Long, Zeiler and Bertsche 2016), and complex models need expertise (Mourtzis 2020).

Heilala, Helin and Montonen (2006) claimed QM&S could address non-financial costs and benefits through considering total cost of ownership. However, the ability of QM&S to consider factors other than costs was criticised by Hamzeh et al. (2018), Alfnes et al. (2016) Lindstrom and Winroth (2010), Thomassen et al. (2016), Sambasivarao and Deshmukh (1997), Ordoobadi and Mulvaney (2001), Farooq and O'brien (2012 and 2015), and Roy et al. (2017).

The applicability of QM&S to small businesses through minimising resource use was suggested by Saberi and Yusuff (2012) and Constantinescu, Francalanza and Matarazzo (2015), Cavalieri et al. (2004) and by reducing the cost of testing alternatives by Oppelt, Wolf and Urbas (2015). Although, QM&S still involves a lot of work to set up (Fischer, Obst and Lee 2017) and a large amount of data is required (Chen, Feng and Zhang 2003). The use of QM&S for ETO products was not mentioned in any of the reviewed papers.

QM&S was claimed to be useful at the early stage by Michalos, Makris and Mourtzis (2012), Bornschlegl et al. (2015), Ferrer et al. (2015), Heilala et al. (2006), Salmi et al. (2015), (2016) and (2018) to test alternatives. Nevertheless, according to Chen, Feng and Zhang (2003) and Lechevalier et al. (2018) this was hampered by the large amount of accurate data required.

2.5.2.9 Summary

The results of assessing the QM&S theme against the six criteria for an approach using existing literature are shown in Table 11. The theme was given a score for each criterion based on the number of papers mentioning strengths and weaknesses. The scoring loosely follows the convention set out in Table 15 for Analytical Hierarchy Process, with 1 being equal significance, and 9 being absolutely more significant. As negative numbers are not possible, this was adjusted so that 5 was the baseline and a criterion that had more papers describing it as a weakness was given a score of less than 5, while those with more papers describing strengths were given a score higher than 5.

The majority of authors supported QM&S for rapid application, claiming that it was fast due to computerisation and reduced the time of testing alternatives. The consensus was that this theme is not easy to use due to the knowledge and experience required, the large amount of work to set up and the difficulty of acquiring data. Additionally, many authors remarked upon the inability of QM&S to take into account non-financial costs and benefits. Several authors targeted SMEs by reducing resource requirements for their approach, although others mentioned the large amount of work and data required. No reviewed papers covered the application of QM&S to ETO products so the theme was given a low score for this criterion. This could have been allocated a 5 with this adjusted scoring system but this could have made the theme comparatively higher than another theme without any evidence. Finally, the theme was found to be usable at the early stage of planning by several authors, who mentioned the ability to test alternatives, although the data required can be difficult to collect at this early stage.

Table 11: Quantitative modelling and simulation scores for the criteria supported by literature.

		Quantitative modelling and simulation	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	9	Fast - Bradford (2000), Heilala, Helin and Montonen (2006), Shehabuddeen et al. (2006), Guschinskaya et al. (2011), Busogi et al. (2017), and Salmi et al. (2018), reduced time of testing alternatives - Oppelt, Wolf and Urbas (2015)	Long computer processing times - Salmi et al. (2018)
Usable	1	Simple graphical user interface - Rahman and Mo (2012b), ease of use -Bertolini, Esposito and Romagnoli (2020),	Knowledge and experience still needed - Ng, Urenda and Svensson (2007), acquisition of data difficult - Wuest et al. (2016) and Lechevalier et al. (2018), lot of work to set up - Fischer, Obst and Lee (2017), Petri nets can become unmanageably large - Kim and Lee (2013) and Long, Zeiler and Bertsche (2016)
Non-Financial	1	Total cost of ownership - Heilala, Helin and Montonen (2006)	Criticised by - Hamzeh et al. (2018), Alfnes et al. (2016) Lindstrom and Winroth (2010), Thomassen et al. (2016), Sambasivarao and Deshmukh (1997), Ordoobadi and Mulvaney (2001), Farooq and O'brien (2012 and 2015), and Roy et al. (2017),
Resources	7	Small business - Saberi and Yusuff (2012) and Constantinescu, Francalanza and Matarazzo (2015), reduce the required resources - Cavalieri et al. (2004), reduce cost of testing alternatives - Oppelt, Wolf and Urbas (2015)	Lot of work to set up - Fischer, Obst and Lee (2017), large amount of data required - Chen, Feng and Zhang (2003),
ETO	1	-	-
Early stage	9	Useful at the early stage - Michalos, Makris and Mourtzis (2012), Bornschlegl et al. (2015), Ferrer et al. (2015), Heilala et al. (2006), Salmi et al. (2015), (2016) and (2018),	Large amount of accurate data required - Chen, Feng and Zhang (2003), Lechevalier et al. (2018)

2.5.3 Database decision aids

Another theme identified in literature is that of database decision aids (DDAs) and tools which attempt to assist the decision maker by providing knowledge to help in their choices. These were proposed as far back as Boothroyd and Dewhirst (1983) and Sambasivarao and Deshmukh (1995 and 1997) who created decision support systems, but the idea is still being improved upon. Recent papers from Ramis et al. (2015) on process and resource mappings, Savoretti et al. (2017) with a life cycle cost estimation tool and Hamzeh et al. (2018) with their technology selection framework show that the idea is still in use although it has not yet been perfected.

DDAs speed up the development of new systems according to Ramis et al. (2015), Sambasivarao and Deshmukh (1997), Savoretti et al. (2017). No reviewed authors criticised DDAs for rapid application. Ramis et al. (2015) claimed that DDAs could make the automation process more accessible and Hamzeh et al. (2018) stated they are an easy to understand tool. However, the experience of users was found to affect performance by Shehabuddeen, Probert and Phaal (2006).

The use of DDAs to include non-financial costs and benefits was championed by Asawachatroj et al. (2012) through real benefit calculation, Hamzeh et al. (2018) using risk calculation, Sambasivarao and Deshmukh (1995 and 1997) by considering human, social, and strategic factors, and Goh et al. (2020) considering variability. No reviewed authors claimed weaknesses of DDA in considering non-financial costs and benefits. Conversely, no reviewed authors mentioned strengths of DDA for small business/resources but Hamzeh et al. (2018) contested that many approaches could not be scaled down. Likewise, no strengths of DDA for ETO products were identified in literature but the weakness of selecting from too many alternatives was highlighted by Savoretti et al. (2017). Finally, a strength of DDA at the early stage according to Savoretti et al. (2017) was its use to minimise the danger of choices increasing the cost of implementations.

Papers that mention the criteria have been gathered in Table 12, to help assess the strengths and weaknesses of this theme. As there were fewer papers overall for the DDA theme than QM&S, a smaller number mentioned the six criteria but some results can still be inferred. Approaches in the DDA theme were fast, usable by managers and at the early stage, and excelled at considering not just the financial costs and benefits. With limited evidence, the theme received lower scores for use of resources and being applicable to ETO products.

Table 12: Database decision aid scores for the criteria supported by literature.

		Database decision aids	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	8	Speeds development of new systems - Ramis et al. (2015), Sambasivarao and Deshmukh (1997), Savoretti et al. (2017)	-
Usable	6	More accessible - Ramis et al. (2015), easy to understand tool - Hamzeh et al. (2018)	Experience of users affects performance - Shehabuddeen, Probert and Phaal (2006)
Non-Financial	9	Real benefit calculation - Asawachatroj et al. (2012), risk calculation - Hamzeh et al. (2018), consider human, social, strategic - Sambasivarao and Deshmukh (1995 and 1997), considers variability - Goh et al. (2020)	-
Resources	4	-	Many approaches cannot be scaled down - Hamzeh et al. (2018)
ETO	4	-	Selecting from too many alternatives - Savoretti et al. (2017)
Early stage	6	Choice implications for cost - Savoretti et al. (2017)	-

2.5.4 Flowchart modelling

The theme termed flowchart modelling consists of approaches that are non-quantitative and use graphical modelling such as IDEF0. Wang, Tang and Li (2010) and Rahman and Mo (2010 and 2012a) used IDEF0 to map production processes and identify areas for improvement and Roy et al. (2011) used it to identify cost elements necessary to calculate the cost of automation projects at an early stage. IDEF0 was proposed by Jung et al. (2017) for factory modelling to show the connections between activities and also the information and software relied on by each activity. They used this to improve existing factories as well as create designs for new factories but their work was limited to information system and procedural changes. Industrial value chains were modelled by Wang, Tang and Li (2010), using IDEF0 to map activities and the relationships between them but did not use it to suggest improvements.

Flowchart modelling was claimed to aid quick reconfiguration by Ang (1999), Perera and Lyanage (2000), Rahman and Mo (2010 and 2012a) and no arguments were made that suggested the flowchart theme to be time consuming. The usability by managers was identified as a strength by Gingele (2001) through use of common language, and Jung et al. (2017) by organising tasks and information. Wehrmeister et al. (2014) claimed flowcharts reduce experience requirements and Erasmus et al. (2020) stated they were easy to use. Contrary to this however, De Felice, Petrillo and Zomparelli (2018b) found that experienced and knowledgeable users were needed to develop a flowchart but minimising human interaction can reduce errors.

The use of flowcharts to consider non-financial costs and benefits was examined by De Felice, Petrillo and Zomparelli (2018b) using organisational, technical and human factors but the lack of consideration for quantities was identified by Seth et al. (2017) as a weakness. Flowcharts can minimise use of resources for small businesses using a company wide approach according to Qurashi (2000) and Rahman and Mo (2012a) claimed that flowcharts minimise costs. Seth et al. (2017) found that flowcharts can be useful in ETO production through simplifying and approximating data and another strength according to Thomassen, Alfnes and Gran (2015) was considering the customer order decoupling point. One of the greatest strengths of flowcharts was at the early stage of planning (Fast-Berglund and Stahre 2013). Flowcharts can identify cost elements at early stage (Roy et al. 2011), and reduce data requirements, making data available (Mazak and Huemer 2015).

The papers that specifically mentioned the criteria for an approach are gathered in Table 13 and showed support for the Flowchart theme for each criterion except considering non-financial costs and benefits, for which it achieved only a score of five. Therefore, in literature this theme was lauded as being rapid, usable by managers, having low resource use, and was applicable to ETO products as well as at the early stage of planning.

Table 13: Flowchart scores for the criteria supported by literature.

		Flowchart	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	8	Quick reconfiguration - Ang (1999), Perera and Lyanage (2000), Rahman and Mo (2010 and 2012a),	-
Usable	8	Common language - Gingele (2001), organising tasks and information - Jung et al. (2017), reduce experience requirements - Wehrmeister et al. (2014), easy to use - Erasmus et al. (2020)	Experienced and knowledgeable users needed but can minimise human interaction to reduce errors - De Felice, Petrillo and Zomparelli (2018b)
Non-Financial	5	Organisational, technical and human factors - De Felice, Petrillo and Zomparelli (2018b)	Quantities not considered - Seth et al. (2017)
Resources	7	Company wide approach - Qurashi (2000), Minimising cost - Rahman and Mo (2012a),	-
ETO	7	Simplify and approximate data - Seth et al. (2017), considering the customer order decoupling point - Thomassen, Alfnes and Gran (2015)	-
Early stage	8	Useful for planning - Fast-Berglund and Stahre (2013), identify cost elements at early stage - Roy et al. (2011), reduce data requirements, making data available - Mazak and Huemer (2015)	-

2.5.5 Consultancy/Tools for cost and time calculation

The consultancy/tools for cost and time calculation theme is widely used in industry and can be found in government literature such as the Rural Development Alberta Automation Assessment (no date). To highlight the challenges Chen and Small (1996), published a future research framework around planning for AMT and concluded that the key challenges are choosing an appropriate AMT system and making sure the infrastructure of the organisation can support the chosen system. Recent research from Salim, Manduchi and Johansson (2020) shows that this issue has still not been solved. They examined the automation of a wood manufacturing company through the meetings, emails, project documents and interviews with participants. Their findings were that low knowledge of automation led to uncertain requirements and reliance on suppliers. This led to reduced involvement in specification development and less awareness of the benefits of automation that diminished the potential reward.

A weakness of consultancy methods is their lack of rapid application as existing methods are time consuming according to Thomassen, Sjøbakk and Alfnes (2014), and many discussions and meetings required (Rother and Shook 1999). The general consensus among reviewed authors was that consultancy methods are not usable by managers with technical knowledge as they are difficult (Thompson 1995), low knowledge leads to reliance on suppliers (Salim, Manduchi and Johansson 2020), rely on knowledge of user (Baines 2004, Sutherland and Baker 2007, Thomas, Barton and John 2008, Fulton and Hon 2010), and a team of experts was required according to Sinnwell, Krenkel, and Aurich (2019). However, this can be mitigated through an easy to apply method (Thomassen, Sjøbakk and Alfnes 2014), by reducing complexity (Stähr, Englisch and Lanza 2018), or through testing on untrained participants (Fast-Berglund and Stahre 2013).

Consultancy is strong in considering non-financial costs and benefits through examining company wide costs (Larsen 1994), discussing and voting on factors (Ordoobadi and Mulvaney 2001), including quality and lead time (Hamzeh et al. 2018), considering other potential benefits (Salim, Manduchi and Johansson 2020), and using strategic criteria (Chan et al. 2001). Other researchers were split fairly evenly on the strengths and weaknesses of consultancy for small business through minimising resource use. Bradford (2000) and Rahardjo and Yahya (2010) focussed on SME's, and their lack of knowledge and financial resources was addressed by Ordoobadi and Mulvaney (2001). Conversely, the high resource cost of consultancy was detailed by Teufl and Hackenberg (2015) and Qin, Liu and Grosvenor (2016).

The use of consultancy methods for ETO products was focussed on by Adrodegari et al. (2015) and Thomassen, Alfnes and Gran (2015) and no authors mentioned weaknesses of consultancy for ETO products. Finally, the consultancy theme was found to be useful at the early stage by Fast-Berglund and Stahre (2013), Teufl, and Hackenberg (2015), by involving all parties from the start and drawing in information and by Sinnwell, Krenkel, and Aurich (2019) through system design using early product information.

The papers that explicitly mentioned the six criteria are gathered in Table 14, and show low support of the theme for the rapid application and usable by managers criteria. However, strong support was given in literature for the consultancy theme in the not just financial costs and benefits, ETO and usable at the early stage of planning criteria. The resource use and applicability to small businesses of the theme was less supported by still positive.

Table 14: Consultancy/tools for cost and time calculation scores for the criteria supported by literature.

		Consultancy/tools for cost and time calculation	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	3	-	Existing approaches time consuming - Thomassen, Sjøbakk and Alfnes (2014), discussions and meetings required - Rother and Shook (1999)
Usable	1	Easy to apply method - Thomassen, Sjøbakk and Alfnes (2014), can reduce complexity - Stähr, Englisch and Lanza (2018), testing on untrained participants - Fast-Berglund and Stahre (2013)	Difficult - Thompson (1995), low knowledge leads to reliance on suppliers - Salim, Manduchi and Johansson (2020), relies on knowledge of user - Baines (2004), Sutherland and Baker (2007), Thomas, Barton and John (2008), Fulton and Hon (2010), team of experts required - Sinnwell, Krenkel, and Aurich (2019)
Non-Financial	9	Company wide costs - Larsen (1994), can be discussed and voted on - Ordoobadi and Mulvaney (2001), quality and lead time - Hamzeh et al. (2018), consider other potential benefits - Salim, Manduchi and Johansson (2020), strategic criteria – Chan et al. (2001)	-
Resources	6	Focus on SMEs - Bradford (2000) and Rahardjo and Yahya (2010), Address lack of knowledge and financial resources - Ordoobadi and Mulvaney (2001)	High resource cost of building the diagram - Teufl and Hackenberg (2015) and Qin, Liu and Grosvenor (2016)
ETO	7	Focus on ETO - Adrodegari et al. (2015) and Thomassen, Alfnes and Gran (2015)	-
Early stage	8	Involves all parties from start and draws in information - Fast-Berglund and Stahre (2013), Teufl and Hackenberg (2015), system design using early product information - Sinnwell, Krenkel, and Aurich (2019)	-

2.6 Summary

Many different directions have been attempted to attack the problem of automated manufacturing system specification. Through systematic examination of the literature around implementation of automated manufacturing systems, useful criteria for an approach and themes of existing research have been identified. The criteria discovered as important for an approach to implement an automated system are: *rapid application, usable by managers with technical knowledge, consider not just the financial costs and benefits, resource use, for engineer to order (ETO) products,* and *useable at the early stage of planning*. The four themes identified were; *quantitative modelling and simulation, database decision aids, flowchart methods* and *consultation/tools for cost and time calculation*. These themes were compared with respect to the identified criteria to yield useful information about their strengths and weaknesses to aid in choosing between themes.

Quantitative and computer modelling methods provide the hard numbers that companies require to plan projects, but struggle to consider intangible factors and rely heavily on input data availability and quality. Database decision aids allow the reuse of knowledge and experience, however developing and keeping the database up to date requires resources. Flowcharts are excellent for presenting current and planned systems in an understandable way; unfortunately, they rarely take into account quantities or time (except in the special case of VSM). The consultancy/tools for cost and time calculation theme benefits from assisting the flow of knowledge and experience between stakeholders resulting in better decisions. However, it can be prone to practitioner bias and success can be dependent on the knowledge and experience of the users. These consultancy tools can also suffer from their iterative nature preventing a project from progressing at the desired speed.

All of the research included in this chapter presented either criteria for or solutions to aspects of the specification of automated manufacturing systems problem. Each has strengths and weaknesses that have been highlighted through the literature review in Table 11, Table 12, Table 13, and Table 14. Chapter 4 expands on this using the criteria to assess the relative merits of each theme. Existing research was critically evaluated by determining its usefulness in achieving the criteria. The most promising theories from literature were tested empirically using small experiments in a host company. The next Chapter discusses the author's philosophical viewpoint, methodology and methods for this research.

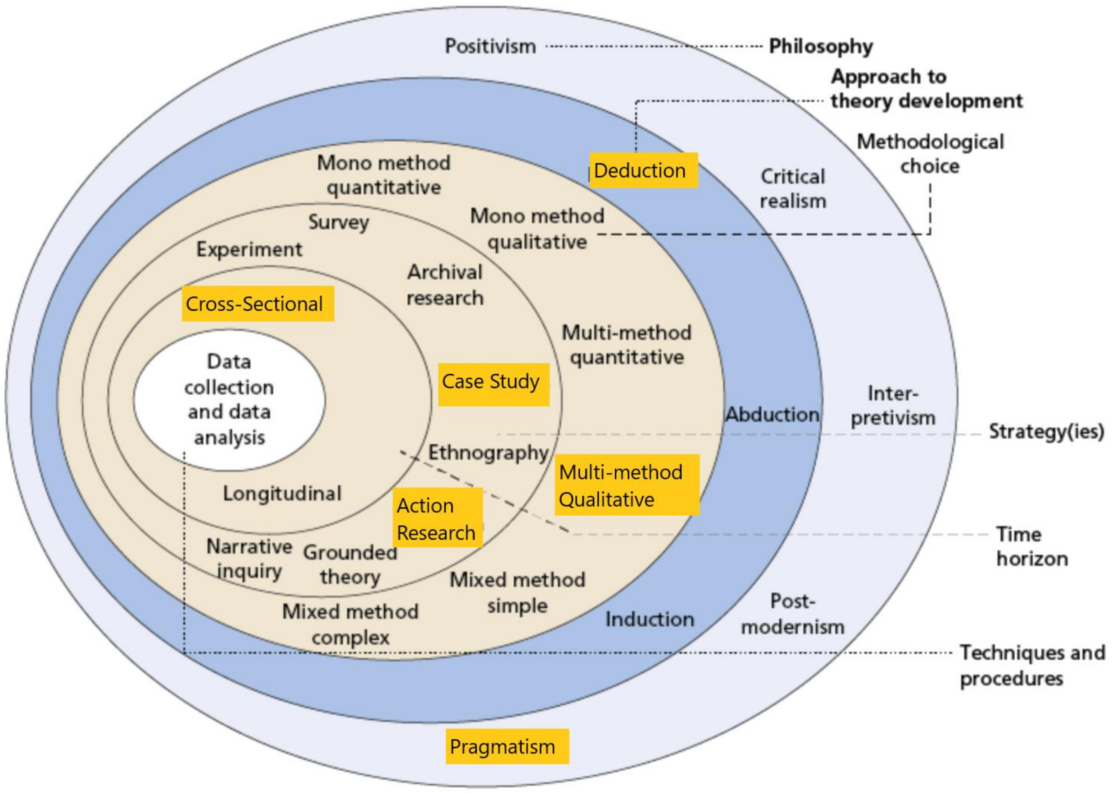
3 Research methodology

3.1 Introduction

This Chapter describes the methodology used to carry out the research and the reasons for the methodological choices of the author. To do this, it is also necessary to describe the alternative methodologies and the basis for discounting them. The chosen methodology must also fit the research question "*How can an approach specify automated manufacturing systems?"*. The structure of the Chapter is, firstly a discussion of the author's research philosophy, followed by data collection, investigative and experimental methods and then data analysis. At the end of the Chapter is a short summary of the main points.

3.2 Research methodology development

A tool to illustrate the methodology development process is the research onion shown in Figure 2, which was developed by Saunders, Lewis, and Thornhill, (2016). This aids the researcher in defining their methodology by moving from the outside layer inwards, building towards more detailed stages of the research process and was chosen due to its ease of use and familiarity for among researchers. The chosen route is highlighted in yellow and the choices are detailed in the following sections.



Source: ©2018 Mark Saunders, Philip Lewis and Adrian Thornhill

Figure 2: Research Onion adapted from Saunders, Lewis, and Thornhill (2016).

An alternative model is that of Meredith (1989) who proposes a two dimensional framework (Figure 3) to aid researchers in choosing methods appropriate to their research philosophy. This was not used by the author but it is interesting to work backwards from the methods used to see if the methods were valid. The author used interviews, surveys and experiments, which are in the centre but slightly towards rational and artificial. This fits reasonably well with the authors research philosophy of pragmatism discussed in the next section.

NATURAL ⟷ ARTIFICIAL

RATIONAL ↕ EXISTENTIAL

	DIRECT OBSERVATION OF OBJECT REALITY	PEOPLE'S PERCEPTIONS OF OBJECT REALITY	ARTIFICIAL RECONSTRUCTION OF OBJECT REALITY
AXIOMATIC			• REASON/LOGIC/ THEOREMS • NORMATIVE MODELING • DESCRIPTIVE MODELING
LOGICAL POSITIVIST/ EMPIRICIST	• FIELD STUDIES • FIELD EXPERIMENTS	• STRUCTURED INTERVIEWING • SURVEY RESEARCH	• PROTOTYPING • PHYSICAL MODELING • LABORATORY EXPERIMENTATION • SIMULATION
INTERPRETIVE	• ACTION RESEARCH • CASE STUDIES	• HISTORICAL ANALYSIS • DELPHI • INTENSIVE INTERVIEWING • EXPERT PANELS • FUTURES/ SCENARIOS	• CONCEPTUAL MODELING • HERMENEUTICS
CRITICAL THEORY		• INTROSPECTIVE REFLECTION	

Figure 3: Framework for research methods (Meredith 1989)

3.2.1 Research philosophy

3.2.1.1 Introduction

Research philosophies are also referred to as paradigms or epistemologies (Eriksson and Kovalainen, 2016). The choice of research philosophy defines how the researcher thinks about the world. When considering which philosophy to use it is necessary to consider each alternative and accept or reject it in a logical way and then describe the thought process that resulted in the decision. A description of each and the reasons for rejecting or accepting follows.

3.2.1.2 Positivism

Positivism, which comes from the work of Francis Bacon and Auguste Comte (Gunn, 2002), deals with strictly scientific empirical methods to produce pure data and facts with no influence from bias or human interpretation. The essence is that only observable and measurable phenomena yield data that can be examined to find causal relationships to use in generalisations according to Saunders, Lewis, and Thornhill, (2016). Although this philosophy is widely used and accepted, it was not suitable for this research as many of the variables were not directly measurable and instead relied on the views of managers involved in the process. This required human interpretation that was subject to bias. In addition, the specification of automated production machines is too complex and variable to define only in a mathematical formula.

3.2.1.3 Critical realism

Critical realism, based on the idea that what we experience through our senses is an accurate representation of the world was popularised by Roy Bhaskar (1978). Researchers try to find causes and mechanisms of observable events typically by analysing social structures to see changes over time (Reed 2005). This research had to be cross-sectional rather than longitudinal due to time restrictions and the limitations of access to participants so this paradigm was not possible. However, critical realism requires awareness of the influences of the researchers own views and bias so that they can be minimised and this was necessary when analysing data.

3.2.1.4 Interpretivism

Interpretivism, which originated in Europe in the middle of the 20th Century, concentrates on the idea that people create meanings as opposed to physical phenomena, which do not

(Saunders, Lewis, and Thornhill, 2016). This requires the study of processes involving people to be different to study of natural science. Interpretivists argue that valuable knowledge about humanity is not possible by reducing it to law like generalisations. For example, we can look at the problem from the perspectives of different people from the CEO down to the office cleaner (Saunders, Lewis, and Thornhill, 2016). This study focussed on the views of the manager who is implementing automation and their reality was the one investigated. However, it was necessary to be aware of the missing views of other stakeholders in the automation process such as factory workers and customers and the influence of the author's views to combat bias. This paradigm does not completely fulfil the needs of this investigation, as factors other than the opinions of managers were important such as the relative benefits of physical manufacturing systems measured in monetary cost and cycle times.

3.2.1.5 Postmodernism

Postmodernists emphasise the importance of language in defining categories and classifications on the chaotic world (Chia 2003). However, they are aware of the limitations of language as it can only partially describe phenomena and may not address all aspects. Researchers can find truth by considering the views of multiple parties but the power relationships between individuals also influence them. This can result in exclusion of some views resulting in incomplete knowledge (Foucault, 1991). Post modernism then challenges these established views and looks at the unheard voices and opinions. It could have been useful in this research to bring in the views of less senior workers on the automation of manufacturing. However since automation is viewed as a threat to their jobs by factory workers their input could be subject to bias or even deliberate misinformation. Classification of automated processes is certainly useful to fulfil the aims of this research, by imposing order on the components, but does not fully encompass the problem.

3.2.1.6 Pragmatism

Pragmatism as a paradigm began around 1870 with William James and Charles Sanders Peirce. John Dewey and Jane Adams then further developed it to encompass politics and social improvement (Legg and Hookway, 2019). Kelemen and Rumens (2008) tell us that Pragmatists only consider concepts that support action to be relevant. Pragmatism is problem centred, grounded in the real world and concerns the consequences of actions. The researcher chooses whichever methods best meet their needs. What works is the truth and the researcher does not get involved with the duality of reality independent of the mind or within the mind and Pragmatists consider intended consequences when deciding what and how to research according to Creswell, (2014). These qualities suit the primary research question, which targets a problem in the real world.

Pragmatism combines the facts and accurate knowledge of positivism with the in depth experiential data of interpretivism. Researchers begin with a problem and try to come up with practical solutions to it through a value driven process that changes their doubt about something to belief through solving it (Elkjaer and Simpson 2011). The most important factor when deciding methodology is the research problem itself and not the abstract definitions of positivist or interpretivist. This resonates most strongly with the author, as research should solve practical problems and this research journey began with the problem of how to decide which automation to implement and indeed whether to automate at all. Another benefit is that whichever methods suit the data gathering at the time can be used (Keleman and Rumens 2008).

3.2.2 Theory development

Three approaches to theory development are accepted: deduction, induction and abduction. The deductive researcher starts with a theory and tests it through a careful research strategy. On the other hand, the inductive researcher begins by collecting data on a subject and attempts to build theory from it. The abductive researcher starts with a phenomenon, collects data to generate new theory, and then tests it through collecting more data, moving between induction and deduction (Saunders, Lewis, and Thornhill, 2016). This research project was deductive as the author firstly looked for existing theory in literature and then attempted to test the most promising parts and validate them through data gathering. While this approach is fast and relatively easy compared with inductive research, it can potentially bias analysis through inflexibility created by deciding the themes in advance according to Burnard et al. (2008).

3.2.3 Methodological choice

The focus of quantitative research is looking at the relationships between numerically measured variables using statistical and graphical methods (Saunders, Lewis, and Thornhill, 2016). This is echoed by Cresswell (1994 p2) who says that a quantitative design investigates a problem based on theory with variables that can be numerically measured and statistically analysed to test its generalisations. In this research, many of the important variables to consider, for example ease of use of an approach, were difficult or impossible to measure numerically making statistical analysis inappropriate. Another reason to discount Quantitative methods is that the data they gather is broad and shallow and the data required to fully explore this research problem was more narrowly focussed and deep such as the experiences of managers involved in specification of automation. Multi-method is the use of more than one qualitative or quantitative method without mixing them, which Bryman (2006) claims will mitigate the weaknesses of single methods.

Denzin and Lincoln (2011) describe the research philosophy of qualitative research as interpretive, as the researcher tries to analyse the subjective descriptions of the subject gleaned from participants. The researcher then produces a conceptual framework, which can yield a contribution to theory (Saunders, Lewis, and Thornhill, 2016). Success can depend on the researchers' ability to build relationships to gain access to participants' opinions. The author used semi-structured interviews to gather the views of managers on automation implementation. Mini case studies of real implementations of automation were then undertaken to test ideas and validate the chosen methods. This was multi-method qualitative, as no quantitative methods were be used.

Exploratory studies use open questions to find out about the subject and may even show that it is not worth researching. Methods include literature review, expert interviews, or focus groups and this fitted the author's research aims well. Descriptive studies try to give a true picture of the subject, but this is not enough and the researcher must go further to analyse the findings and explain them. Explanatory studies attempt to find relationships between variables and explain them, which does not apply well to qualitative research as variables are often not clear. Evaluative studies attempt to work out the quality of a process and were used in this research once approaches were identified, to test and validate them.

3.2.4 Research strategy

According to Yin (2014), a case study is a deep investigation of a subject in its real-life environment whose boundaries are determined by the researcher. They also tell us that case studies are often used when the boundaries between the object of investigation and its context are not clear and understanding this is important, as it is very different from experimental strategy where the context is carefully controlled. Case studies can produce deep empirical descriptive information from which theory can develop through intensive research of the subject in its environment (Dubois and Gadde 2002; Eisenhardt 1989; Eisenhardt and Graebner 2007; Ridder et al. 2014; Yin 2014). This was important for this research as the environment in which the implementation of automation takes place has a large effect on the success of the project. For example, the culture of the workplace or the variability of the inputs can make an automation project more difficult through lack of acceptance or inability of suppliers to standardise to the required level of accuracy or precision.

Case study research is criticised by positivists who claim that contributions to knowledge are not generalisable and reliable due to small sample size and general misgivings about qualitative research but many authors refute this (Flyvberg 2011). Case studies can be interpretivist or positivist, inductive or deductive, and exploratory, descriptive or explanatory, creating an advantage for case study research, as many methods are available but also a disadvantage due to multiple methods diluting the study. There is also the decision of how many cases are necessary. Sometimes research only needs a single case, for example when it is unique or because it is typical. More commonly, replication of findings is produced through multiple cases. If the researcher predicts similar findings between cases, this is literal replication and if a factor is different, this is theoretical replication (Yin 2014).

3.2.5 Time horizon

Cross-sectional studies research a phenomenon at a particular time whereas longitudinal studies observe the same phenomenon at different points in time. This research was cross-sectional due to time constraints of the researcher and access to subjects but this meant that the longitudinal advantage of being able to monitor implementation of automation over time was lost.

3.2.6 Research ethics

As a researcher, it is important not to cause embarrassment, pain or harm to those involved in the research. This is tied to consent, as when people are not aware they are taking part in research this in itself can be harmful (Saunders, Lewis, and Thornhill, 2016). This research did not solicit any personal details from those interviewed and all subjects were informed of the purpose of the research before any questions were asked. However, some information gleaned through conversations about actual work projects was used to inform the background knowledge of the author.

3.3 Data Collection

3.3.1 Semi-structured interviews

An interview for research is a conversation between two or more people with the aim of gathering knowledge. The interviewer must create affinity with the interviewee and use clear and purposeful questions to elicit readily given responses according to Saunders, Lewis, and Thornhill, (2016). These responses are listened to carefully and used to expand the conversation further. Interviews can be neopositivist, where the interview is a tool, the interviewee is an observer of independent reality and their answers are treated as factual. However, Qu and Dumay (2011) tell us this ignores the beliefs that filter opinions, which can be addressed by a subjective, or romanticist approach where the data from the interview is socially co-produced by both the interviewee and the researcher who guides the interaction and analyses the results. They regard interviews as "complex social and organizational phenomena", not just a method used in research.

Semi-structured interviews were preferred over structured or standardised interviews as they allow flexibility to acquire knowledge of complex subjects like decision making according to Salim, Manduchi and Johansson (2020). Conversely, completely unstructured interviews were not used, as the questions important for the research may not have been answered. Saunders, Lewis, and Thornhill (2016), advise the use of semi-structured interviews in exploratory studies to reveal the context as the researcher can ask their participant to expand on interesting answers, which adds depth and significance. Additionally, previously unconsidered and interesting ideas may emerge which could be useful to the research. The researcher must take into account that everything they do can influence the data collected. Managers prefer interviews to questionnaires claim Saunders, Lewis, and Thornhill, (2016) as they do not have to write anything down. They will also be more likely to disclose sensitive information, and when an interviewee declines to answer a question, they will often give a reason, which can again be useful for the research.

Some major issues around interview method are highlighted by Kvale (2006), particularly the possible asymmetry of power between interviewer and interviewee. This must be recognised to prevent poor objectivity and to prevent unethical practices. Memorably they compare some interviewers to the wolf in "Little Red Riding Hood" as they breach their subjects' defences with their caring approaches and "big eyes and ears" to solicit information. Another issue highlighted by Saunders, Lewis, and Thornhill, (2016) is for data quality to be affected by interviewer bias caused by comments, verbal tone or non-verbal cues when asking questions and interpretation when analysing responses. Interviewee bias due to their sensitivity about certain ideas may cause them to give answers, which do not reveal their true opinions. Participation bias is caused by the sample of people who agree to be interviewed and can be mitigated by carefully considering sample selection. This research was subject to participation bias as the opportunities for interviews with key managers was limited. It can be argued that the interview does not need to be repeatable as it is a snapshot of that moment, however to ensure rigour the reasons for research design choices must be explained.

Preunderstanding according to Gummesson 1991 refers to the authors knowledge and thoughs about the problem before beginning to research it. He refers to preunderstanding as the input to the research and the output is understanding. The author began this research with a small amount of experience in the automation field and this guided the early research direction and forming of the questions to be answered. As the project progressed this was added to with the preunderstanding of other researchers through literature review. One problem with this is that academics have little experience of management in a specific industry or company (Gummesson 1991).

3.3.2 Survey

The survey method was piloted to elicit the views of managers on the criteria for an approach to specify automated manufacturing systems. The tool used was smartsurvey.co.uk as this allowed free use for a limited number of questions and participants. The survey involved 10 questions answered on a Likert scale from strongly disagree to strongly agree. The survey questions and the results can be found in Appendix A. Results of the survey were unfortunately not useful as they aggregated to “agree” for all questions. This was due to the design of the survey with all questions being generally agreeable. A change of format so that each question involved ranking importance of several criteria to the user was designed (Appendix A). However, this was not used, as access to participants would have required more resources than those available.

3.4 Investigative and experimental methods

3.4.1 Preliminary study

A scoping investigation was the logical first step to guide the development of aims and research questions similar to that used by Rauch et al. (2020) but limited to one company. This began with interviews of primary users at the host company such as the managing director, sales engineers and mechanical and software design engineers. This used a mix of open and closed questions to illicit opinions and views from experienced automation practitioners. The answers given were simply analysed for common ideas and problems, which were used as the basis for the direction of the research and a specification for the solution required (described in further detail in Results Chapter).

3.4.2 Literature review

Review of literature began around general search terms such as 'automation specification', 'modelling production automation'. A full description of the review method can be found at the start of the Literature Review Chapter. Through reading and following references discovered, the search terms became narrower and more specific. This resulted in a collection of around two hundred papers that were about the specific problem. These were then examined further and codified for recurring themes. From these four promising themes emerged; quantitative modelling and simulation, database decision aids, flowchart modelling, and consultation. The methods used to experiment with these are described in the following sections. Analysis of the gathered research also revealed criteria important in an approach to specify automated production systems. These were used to aid in criticising the identified themes in the Results Chapter.

3.4.3 Experimental environment

The experiments were conducted through the author's role as an automation engineer in a controls and automation company. Working on varied automation projects for customers allowed observation of current procedures and testing of ideas from literature while defining the boundaries of the study and highlighting important factors. Examples of this were the criteria for an approach, which became apparent during review of literature and through experiences with customers and consideration of the characteristics of the host company. As with many customer driven industries, time demands are often difficult to achieve and this reinforces the need for rapid application of an approach.

The company was a small one of around 50 employees, which required all employees to learn many skills outside of their specialisations. This necessitates an approach that is easy to learn and does not require specialist knowledge. The automated production systems that were the main product of the company are expensive to produce because of both the high cost components and the large amount of time needed by experienced engineers, which means there is a large investment from the customer and to justify this often the financial arguments are not enough. This is why it is necessary to consider not just the financial costs and benefits. While automation-planning solutions exist for large companies, which involve expensive software and teams of engineers, smaller companies do not have the resources required, so an approach is needed for small businesses to fill that gap. The automation systems produced can be considered one of a kind or engineer to order (ETO) products.

3.4.4 Testing

To help improve the methods created in the experiments and to validate them they were subjected to exploratory testing by untrained participants. Exploratory testing (ET) is a term from software development where it is defined as "Simultaneous learning, test design, and test execution" according to Itkonen and Rautiainen (2005) and this is explained as unscripted and without using pre-defined test cases (Itkonen and Rautiainen, 2005, Micallef, Porter and Borg, 2016, and Itkonen, Mantyla, and Lessenius, 2016). ET was partly used due to the author's unfamiliarity with software testing design but yielded useful ideas for improvements to the GUI and functionality of the tools developed. Test results may vary due to the knowledge of the tester but according to Itkonen, Mantyla, and Lessenius (2016) most of the errors identified were straightforward to reveal. This was corroborated by the simple problems found by testers in the author's software tool.

3.4.5 A modelling tool to evaluate potential system performance using QM&S

Although many methods of QM&S have been designed in literature they all consist of the same basic components. Data is entered, processed, and presented to enable analysis, although the acquisition of data and use of the results are not always addressed. Excel spreadsheets were chosen for part of the tool as they are mentioned in several studies, widely available and familiar to most workers. These were used as the data input and result display medium and an 'off the shelf' automation simulation program written in Python was linked to do the data processing. This required quite a large amount of coding in Microsoft Visual Basic and Python, mainly to make the data entry user friendly, present the data in the correct format to the simulation, and convert the result into graphical and tabular forms. The prototype tool was improved by giving it to an untrained subject with very limited knowledge of the process to observe the problems they encountered with data entry. These issues were then fixed by changing the way some data was input and providing more help to the user in the form of tooltips. Once a working software tool had been developed it was tested by attempting to model and simulate production processes found on the popular 'How it's made' television program. These attempts revealed flaws and inadequacies in the tool, which were then improved upon through further coding. Finally, the tool was used to model actual machines produced by the host company in the past. The results of these tests were then used to validate the tool but unfortunately found the data to be of minimal use. Results are explained in detail in the Section 4.2.1 A modelling tool to evaluate potential system performance.

3.4.6 Database decision aids

At the most basic level database decision aids involve using past data to aid in prediction of future results. The authors' experiment with this approach began with the collection of records from past automated machine projects of the host company. These were kept on a server and organised by job number and chronologically. Only records from the preceding two years were considered due to the rapid evolution of technology in the automation industry and the change in costs due to inflation. The data comprised quotes and lists of purchased parts and was entered into a spreadsheet with one row for each project and the costs categorised into an expanding list of categories from labour and material to rotary turntables. Similar devices/applications were grouped in columns. The mean, median and standard deviation were then calculated and analysed. The results of this experiment are described in detail in the Section 4.2.2 Database decision aids.

3.4.7 Flowchart modelling

Many flowchart methods are available and most have been exhaustively researched to demonstrate their potential and expose their limitations. The various approaches are described in detail in Section 3.4.7 Flowchart modelling. The author was able to use a flowcharting method to model the current flows of data and material within an actual automation integration company and develop a plan for the future in the same format. Data was gathered through group discussions, individual interviews, physically 'walking the line' and examination of data. These were set down in a flow chart that began at a top-level overview and gradually deconstructed each process down to individual component level. The developed flowchart was then used for further discussions both internally and with external partners to inform a plan for action. Further discussion of these conversations can be found in Section 4.2.3 Flowchart modelling.

3.4.8 Consultation/Tools for cost and time calculation

Another approach to automation specification that is widely accepted in industry but not often discussed in academia is the use of consultancy. Some notable exceptions are critically reviewed in section 2.5.5 Consultancy/Tools for cost and time calculation. Consultancy involves a discussion between the automation company and the customer and follows a linear process involving structured stages but with several feedback loops. To experiment with this strategy the author observed current practice through becoming involved in the quoting and design process, and informally interviewing practitioners. A tool to assist the sales team in developing leads to new projects was then developed and tested. This could be described as a form of action research where the researcher is making a change from within the environment of study and observing the results. More detail on these results can be found in Section 4.2.4 Consultancy/Tools for cost and time calculation.

3.5 Data analysis

3.5.1 Qualitative data analysis

It is imperative that qualitative data analysis is conducted in a methodical and rigorous way to achieve useful results (Nowell et al. 2017). They went on to say that, the ability to demonstrate through recording and disclosing the analysis methods that consistency and precision have been achieved is essential to ensure the research is reliable. Qualitative data collection and analysis is interactive and requires switching between and combining both in an iterative process. The approach was deductive rather than inductive, using existing theory to shape the research rather than building theory from collected data. Yin (2014) tells us that we can use existing theory to help form the data analysis approach but this is debateable, as the theoretical framework can be restrictive when dealing with qualitative data. The author used the theoretical frameworks presented by previous researchers to frame the data analysis by identifying the themes and variables and their relationships. These were tested through comparison with the data collected and further patterns became apparent through collection and analysis, similarly to the process used by Corbin and Strauss (2008).

3.5.2 Thematic analysis

Thematic analysis is the search for themes or patterns that are present in collected data identified by coding in a systematic way. In deductive research, Saunders, Lewis, and Thornhill, (2016) assert that themes from existing theory may allow focussing on parts of the data rather than analysing its entirety. Coding involves categorisation of the data into divisions that have similar meanings according to the purpose of the research. Searching for themes or patterns, which are broad categories that include more than one code, related to each other and the research question is the next stage. Saunders, Lewis, and Thornhill, (2016) also tell us this is not a straight line process and after some initial thematic mapping it may be necessary to remove a theme or introduce a new one, re-code the data, and change the thematic map. The analytical process requires refinement of themes and their connections into a reasoned and consistent structure through re-reading and reorganising the coded data based on its support for the theme. Miles et al. (2014) recommends testing the relationships between themes through trying alternative explanations that are contrary to the suspected link (negative cases). Testing and explaining alternatives increases the rigour of the research and the validity of any conclusions and informs the decisions about further data to gather.

Thematic analysis has the advantages of being highly flexible and providing a rich and detailed analysis (Nowell et al. 2017). It is also relatively easy to learn making it accessible for less experienced researchers. One issue is that there is relatively little literature on thematic analysis, which could influence the ability of researchers to be rigorous. Combined with this is the risk of the methods' flexibility allowing inconsistency when developing themes. This can be mitigated by stating explicitly the epistemological position of the researcher to underpin empirical results.

Another method is pattern matching where theoretical outcomes are used to predict what will be found when analysing the data (Yin 2014). This means that the researcher develops a theoretical framework first and then tests it deductively using gathered data. This fitted with the author's research as several theoretical frameworks were identified from literature that were validated using the data from case studies and semi-structured interviews. The analysis of qualitative data still involves coding and theme building but the theory can inform a set of starting codes and themes that can be used to shape the questions asked during interviews. The sample selection can also be guided by the theory so that the required number and type of cases can be investigated. Codes will still be added or removed dependent on the data gathered from participants. This deductive approach provides themes to look for in the data and guides the search for patterns using the theoretical predictions. Negative examples and alternative explanations for the patterns still need to be sought to ensure rigour.

3.5.3 Analytical hierarchy process

The author used Analytical Hierarchy Process (AHP) to do pairwise comparison of factors within the study allowing ranking of criteria and themes to highlight advantages and disadvantages. This enabled a structured approach to compare the relative importance of criteria and the overall effectiveness of the research themes identified in the Literature Review Chapter 3. AHP was created by Saaty (1977, 1988 and 2012) in the late 1970s to rank options through the Eigenvectors of a matrix containing their pairwise comparisons. The consistency of the comparisons was also measured mathematically using the average eigenvalues. The use of AHP continues with recent papers from Blagojevic et al. (2020) who use it to analyse success factors for technology implementation in the forest industry and Lee et al. (2012) to compare intangible factors when considering technology options. Ease of use and scalability were noted as the two main benefits of AHP by Bertolini, Esposito and Romagnoli (2020), along with not being data intensive, which suited the authors pragmatic research style and the need to rank the criteria and themes. Limitations of AHP identified in literature include interdependence between criteria and the alternatives, as well as inconsistent ranking criteria and judgements from pairwise comparisons (Velasquez & Hester, 2013). An attempt to improve the consistency of pairwise comparisons was made by Ergu et al. (2011) using matrix multiplication theory and vectors dot product to identify inconsistent elements. This was not used in this research due to the low number of analyses performed and the ease of improving the consistency ratio through trial and error. The pairwise comparisons use a 1 to 9 scale illustrated in Table 15.

Table 15: Analytical Hierarchy Process pairwise comparison scale reproduced from Wind and Saaty (1980).

Intensity of Importance	**Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another.
5	Essential or strong importance	Experience and judgement strongly favour one activity over another.
7	Demonstrated importance	An activity is strongly favoured and its dominance is demonstrated in practice.
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed.
Reciprocals if above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	

The authors' first step was to produce a pairwise comparison table comparing each option with each other option and the reasons for each decision in the format shown in Table 16. The pairwise comparisons were then entered into a comparison matrix according to the reciprocal rule from Table 17. An example of this is shown in Table 18, where i and j are the intensities from the comparison table and each column was summed to give w.

Table 16: Pairwise comparison table with reason for each decision.

Option	Intensity for i	Option	Intensity for j	Reason
A	i^1	*B*	j^1	
A	i^2	*C*	j^2	
B	.	*C*	.	
	.		.	
	i^n		j^n	

Table 17: Pairwise comparison matrix.

	j_1	j_2	j_3	j_4
i_1	1	i_1/j_2	i_1/j_3	i_1/j_4
i_2	j_1/i_2	1	i_2/j_3	i_2/j_4
i_3	j_1/i_3	j_2/i_3	1	i_3/j_4
i_4	j_1/i_4	j_2/i_4	j_3/i_4	1
	w_1	w_2	w_3	w_4

The pairwise comparison matrix is then normalised by dividing each cell by the total for its column (w) in the normalised pairwise comparison matrix as shown in Table 18. A useful arithmetical check is that each column sums to 1. This Table is used to calculate the Eigenvalues (λ) by summing each row and dividing by the number of columns (n). These Eigenvalues are the proportional priority of each option and sum to 1.

Table 18: Normalised pairwise comparison matrix.

	j_1	j_2	j_3	j_4	Sum of row divided by n
i_1	$1/w_1$	$(i_1/j_2)/w_2$	$(i_1/j_3)/w_3$	$(i_1/j_4)/w_4$	λ_1
i_2	$(j_1/i_2)/w_1$	$1/w_2$	$(i_2/j_3)/w_3$	$(i_2/j_4)/w_4$	λ_2
i_3	$(j_1/i_3)/w_1$	$(j_2/i_3)/w_2$	$1/w_3$	$(i_3/j_4)/w_4$	λ_3
i_4	$(j_1/i_4)/w_1$	$(j_2/i_4)/w_2$	$(j_3/i_4)/w_3$	$1/w_4$	λ_4
Sum of column	1	1	1	1	1

Once the Eigenvalues have been calculated the consistency of the pairwise comparisons can be checked by calculating the Consistency Ratio (*CR*) *(Equation 3)* and multiplying it by 100 to give a percentage value. If this is under 10% then the comparisons can be considered consistent. If the CR was greater than 10% the pairwise comparisons were adjusted and the CI monitored. This was facilitated by creating a spreadsheet to perform the calculations, allowing any changes to be reflected immediately in the results. To calculate *CR* the Max Eigenvalue is first calculated by summing the Eigenvalues (λ) multiplied by their column totals (w) as shown in Equation 1. This Max Eigenvalue is then used to calculate the Consistency Index (*CI*) by subtracting the number of options and dividing by the number of options -1 as shown in Equation 2. The Consistency Index is the divided by the Random Consistency Index (*RI*) taken from Table 19, which is adapted from Saaty (1988) Chapter 2, Section 5, Table 2-1.

Max Eigenvalue: $$\lambda\max = (\lambda_1 * w_1) + (\lambda_2 * w_2) + \cdots (\lambda_n * w_n)$$ *(Equation 1)*

Consistency Index: $$CI = \frac{\lambda\max - n}{n-1}$$ *(Equation 2)*

Consistency Ratio: $$CR = \frac{CI}{RI}$$ *(Equation 3)*

Table 19: Random Consistency Index table adapted from Saaty (1988) Chapter 2, Section 5, Table 2-1.

Number of Options	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random Consistency Index	**0.52**	**0.89**	**1.11**	**1.25**	**1.35**	**1.40**	**1.45**	**1.49**

Using AHP enabled a logical and well thought out ranking of the factors found through the literature review based on numbers of papers, experimental results and comments from managers. To perform AHP on the results of the literature review the number of papers presenting strengths and weaknesses for each criteria were gathered in a table for each theme. Scores were assigned by starting from five and adding the number of papers mentioning strengths then subtracting the number of papers mentioning weaknesses. Ranking is on an ordinal scale so requires non-parametric statistics.

3.6 Summary

This Chapter was a description of and reflection on the methodological issues for this research. The Chapter began with the research methodology choices, continued with data gathering and analysis, and finished with investigative and experimental methods. The author chose the pragmatic research philosophy as this allows use of multiple methods and concentrates on producing practical solutions to the identified problems. Theory development was deductive as the author firstly looked for existing theory in literature and then attempted to combine the most promising parts and validate them through data gathering. Methodological choice was multi-method qualitative to yield deep and narrow results, and as the important variables did not lend themselves to quantitative analysis. On the time horizon, the research was cross sectional rather than longitudinal due to limited access to participants and available time. The main data gathering tools were semi-structured interviews with managers, and literature review. A survey was piloted but then abandoned due to lack of resources. From the literature review and interviews, the research questions were developed and four themes of research identified. These were each investigated experimentally using the methods recommended in literature to test their effectiveness in an automation of manufacturing environment. The results of these investigations can be found in the next Chapter.

4 Results

4.1 Introduction

This Chapter relates the results of several experiments conducted through the course of the investigation. The experiments are divided into the four themes identified in the Literature Review Chapter and for each the aim and results are reported in Section 4.2. First, a modelling tool to evaluate potential system performance was developed to investigate the QM&S theme. After this, the database decision aid approach was tested using technology selection aids to choose between options. The next experiment was flowchart methods to plan future implementations of automation. Lastly, various tools for cost and time calculation were created to aid in automation sales consultations with customers. These experiments were compared against the criteria for an approach identified in the Literature Review Chapter using analytical hierarchy process in Section 4.3. Finally, a summary assesses and compares the results each section in the conclusions Section 4.4.

4.2 Empirical Results

4.2.1 A modelling tool to evaluate potential system performance

The first experiment was in the QM&S theme. The broad aim was to evaluate modelling and simulation as a tool to aid in specifying an automated production system. Specifically the approach would allow data input through a user-friendly interface, perform some calculations, and output useful results presented in a graphical format that would help engineers choose between different options for automation.

The method for the experiment evolved from discovery of the open source DREAM manufacturing simulation package during the literature review. While useable as a standalone piece of software written in python and running across platforms, the data entry and return functionalities were based on a graphical user interface (GUI) which had not been completed by the authors of the software. This necessitated creation of a new user interface and the chosen software for this was Microsoft Excel. This was due to the availability in most institutions and companies, familiarity of many users and adaptability for the researcher. Full details of the methods used with figures can be found in Appendix D.

The approach was tested by modelling an actual machine that was being produced by the host company. This was no more complicated than the machines that had been modelled from “How It’s Made” (Appendix D) but gave the advantage of being able to compare the results of the simulation with the results of the manual calculations used when planning the machine. When compared the simulation achieved the same results as the calculations performed by the engineers planning the machine. However, this revealed that it was simpler and faster to calculate the cycle time based on summing the cycle times of each process within the machine. These calculations did not take into account incidence of machine failures and the simulation did but only for set failure rates which could also have been included in the manual calculations.

In this case the manual calculations out performed the simulation for ease and speed partly due to the nature of the machine used to compare. This machine had many stations and all were timed to function simultaneously at the same speed. This allows simple summing of the cycle times of each component to get the overall cycle time. However, when commissioning it was found that any failure anywhere on the line would cause the whole line to stop immediately. Many automated systems attempt to overcome this by separating operations with buffers so that if a machine fails there is a period of grace while the buffer to the next operation is used up before the rest of the line stops. Additionally upstream machines can continue to produce and fill the buffer immediately before the inoperable machine. This allows repairs to be quickly made to keep the overall production operating continuously. The downside is that this requires more units of work in progress, which reduces the efficiency of the production, through taking up more space, and costing more money for inventory. This type of system with dynamic changes due to failures of different parts of the machine is not possible to model by simply summing the cycle times of the individual operations. The simulation would have been able to test different sizes of buffers to achieve the optimum balance of robustness and efficiency.

From the results of the experiments and the comments of engineers and managers that were involved the QM&S theme was given scores for each criteria to enable comparison of strengths and weaknesses shown in Table 20. The speed of application in this limited experiment was very fast due to computerisation of the data entry and simulation. The relative simplicity and addition of user instructions also made this experiment usable by managers with technical knowledge. The experiment used freely available software leading to low resource costs. An aspect that this experiment did not address was consideration of costs and benefits other than financial ones. The simulation only considered cycle time, which can be used to calculate cost per product. So even financial costs such as capital investment were not included. The production lines modelled and simulated in the experiment can be regarded as ETO products and the approach was adaptable to each. However, the configuration and data collection stage could be difficult and time consuming. This ties in with the final point, that while QM&S can be used at the early stage of planning to test options the required data may be unavailable, time consuming to collect or inaccurate, making the approach difficult to use.

Table 20: Strengths and weaknesses of QM&S against the six criteria for an approach.

Criteria	Score	Quantitative modelling and simulation Strengths	Weaknesses
Rapid	9	Computerised calculations	Set up and data gathering time
Usable	7	Simple user interface and instructions	Training needed to understand the tool
Non-Financial	1	-	Can't quantify or simulate
Resources	3	Low cost software	Time consuming to develop and modify to application
ETO	2	-	High configuration and data gathering
Early stage	2	Can use product design	Required data often unavailable or inaccurate

4.2.2 Database decision aids

The aim of database decision aids is to support the user in making decisions on what technology to use in an automated machine by providing a framework of which decisions must to be made and a database of information to aid these decisions. The overall aim in this case was creating specifications for new machines faster, easier, and more accurately. Within this, the aim of the experiment was to capture data from past projects of the host company along with information on available new technologies to support planning of future projects.

The tools to be used for creation of a database were again Microsoft Excel spreadsheets, which could be organised into tables to aid sorting and searching. Data was gathered from employees of the host company, sales representatives of suppliers and internet searches on current and new technologies that would be used in automated production equipment. One problem encountered early on was the huge range of component types and alternative options for each component from each supplier, multiplied by the large number of suppliers creating an unmanageable amount of data to store in one spreadsheet (Figure 4). The amount of effort to create this database and then to maintain it due to constant release of new models and technologies would be considerable.

	A	B	C	D	E	F	
1	Action	Sub-Action	Type	Sub-Type	Supplier	Product	Property 1
2	Sense	Presence	Proximity	Capacitive	Balluf		Liquid level
3	Sense	Presence	Proximity	Inductive	Balluf		Detect metal
4	Sense	Presence	Proximity	Magnetic	Balluf		Detect metal
5	Sense	Presence	Photoelectric	Through beam	Balluf		Install at two
6	Sense	Presence	Photoelectric	Reflective	Balluf		Install at two
7	Sense	Presence	Photoelectric	Difuse	Balluf		Install at one
8	Sense	Presence	Weight		HBM		
9	Sense	Presence	Ultrasonic		Balluf		
10	Sense	Presence	Limit switch		Balluf		
11	Sense	Measure	Laser		Keyence		precise
12	Sense	Measure	Vision		Keyence		flexible
13	Sense	Measure	Rotary Encoder		Farnell		measures ang
14	Sense	Measure	Weight		Farnell		measures forc
15	Sense	Measure	Pressure		Balluf		
16	Sense	Quality	Computer Vision	2D Camera	Keyence		flexible
17	Sense	Quality	Computer Vision	3D Camera	PickIt		flexible
18	Control	PLC	Siemens		Siemens		
19	Control	PLC	Allen-Bradley		Allen-Bradley		

Figure 4: Screenshot of attempted database of automation components.

This database was not finished due to the unmanageable number of options available but some attempt was made to categorise the data that was input to it. These categories were actions and sub-actions to make the data easy to understand and organise it in a useful way. Further sub-divisions for type and sub-type were added to allow differentiation of different models within the broader categories. These categories were constructed based on the need of the manager or engineer to create a solution. Their inclusion in a table allowed sorting components by any of the categories to assist in choosing the best option. The work of entering prices for each option was begun but, as many companies do not publish these, their discovery would have been difficult. Prices also change frequently and discounts can be applied in certain situations making the data hard to maintain. One option considered was to enter an approximate price calculated or inferred from similar components pricing. However, this could lead to inaccuracies and would still present a large time investment. Further experiments with databases were conducted and the methods and results can be found in Appendix D.

In this experiment, none of the attempts at creating a database was successful and because of this no framework to guide application was created. The main reason for the lack of success was the unmanageable number of options for automation components and the large amount of associated information. Given more time the final approach of only entering information when needed could have been successful (Appendix D). A framework could have been created to guide creation and use of the databases and detailing the decisions to be made when specifying automation.

The strengths and weaknesses of the DDA theme, assessed through experimenting with approaches and gathering the comments of users in the host company are presented in Table 21. While creation of the database was very time consuming, using it to assist in decisions could be fast. Due to the Excel format, the approach would be highly useable by managers with technical knowledge and low resource use through not requiring additional software, although no testing was done in this experiment due to the incomplete state of the database. Non-financial factors can be included to help managers make decisions by considering properties and specifications of components. The concept of a database for comparing options also fits very well with being useable at the early stage of planning as it provides the information that is often lacking.

The greatest problem for the DDA theme in the specific environment of this research is that of ETO products. Because these are bespoke and one of a kind they often contain components that are only for that specific product, which makes recording them in a database a wasted effort. However, some parts are used on almost all machines regardless of their purpose such as proximity sensors and these would be useful to record. At the opposite end of the spectrum where the same product is produced continually, for example washing machines, a tech database would be unnecessary, as choices about components after the initial design is finalised are generally only upgrades.

Table 21: Strengths and weaknesses of Database Decision Aids.

		Database decision aids	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	5	Computerised lookup	Time consuming data entry
Usable	7	Easy to understand, simple software	Large amount of data required
Non-Financial	9	Properties and specifications can be included	-
Resources	6	Low cost software	Time consuming to develop
ETO	1	-	One of a kind components
Early stage	6	Provides information to help choose between options	Good quality data required

4.2.3 Flowchart modelling

The aim of the flowchart modelling experiment was to test this approach in an industrial setting with a mini case study. Flowcharts enable presentation of information in an easy to understand way, which in turn assists collaboration between stakeholders. They can be constructed by one individual but are most useful when a group works on them together. The author tried to combine and test these methods using an Operations Management based process of flow-charting and design by committee. This was used on a company's internal efficiency project to automate their tool-room. In this experiment, the flowchart was used to set out the current and proposed states of the tool room, where metal parts are machined, at the host company to support implementation of automation. The goals and format of the exercise were decided through group discussions with the company managing director and university advisors along with ideas developed during the literature review. These were to describe the flows of material and information through the factory and define how to implement automation to improve efficiency.

The process began with one to one and group meetings to identify objectives, priorities and alternatives. These were used to create a top-level diagram of the planned future state of the tool room and its external connections termed the TO-BE diagram. This was constructed through an initial group discussion on the aims of the exercise followed by information gathering through observation, questioning of involved parties and examination of supplier literature. The information was then used to construct the 'TO-BE' flowchart (Figure 5) in the diagram drawing software EDraw. This shows the sales and design departments (Oakmount Control Systems Ltd or OCS) on the left and the machining and fabricating departments (Oakmount Precision Engineering or OPE) on the right. The flows of information and material are represented by arrows of different colours. Departments and processes are represented by boxes with a symbol and name. Further details of this experiment can be found in Appendix D.

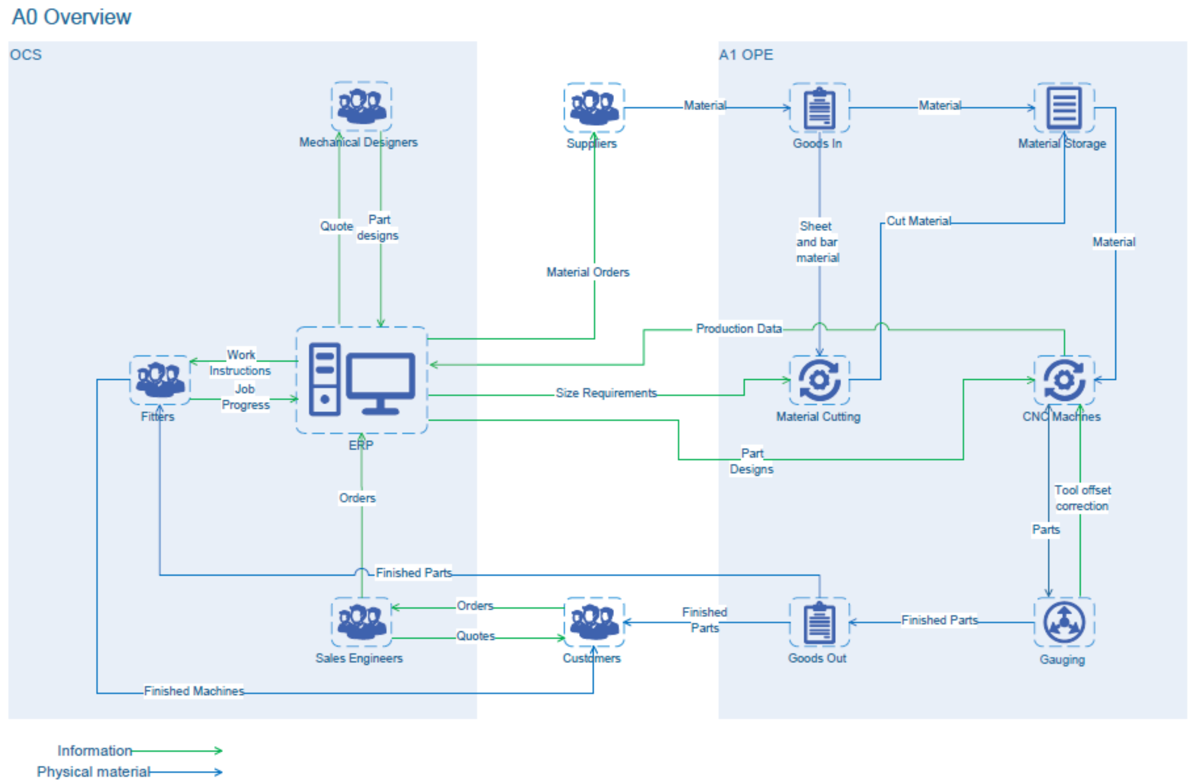


Figure 5: Top-level flowchart showing the proposed or TO-BE state of the tool room and its external connections and the flow of information and material.

Overall, the aims of this experiment were not met, as the proposed changes were never implemented. Some reasons for this are external such as the ERP system not being implemented, lack of management engagement, and the general lack of resources to purchase new equipment. Other factors are due to the tool, the main one being the lack of guidance on where to begin implementation of the proposals. When sharing information in meetings the tool was good at describing ideas in a way that could be easily understood. Group discussions also helped to form the initial diagram and iteratively improve it. The tool was less useful when sharing information via email and resulted in many questions and replies. While good feedback was received on the format, there was no opportunity for group discussion or explanation.

The strengths and weaknesses of the Flowchart theme found through the experiment and comments of those involved are shown in Table 22. The flowchart was not rapid in application due to the large number of meetings and emails required and the slow or no progress achieved. However, this lack of progress could partly be blamed on the lack of resources committed to the project. While the diagrams were easily understood by managers, some knowledge on the subject of the diagram was required to construct them. This was achieved through the authors knowledge combined with that of managers and workers within the business and external experts from companies selling the technologies required. However, using groups to pool knowledge has the disadvantage of high resource use. Non-financial considerations can be included but it is difficult to compare their merits with this approach. It could be used as a tool for showing which costs needed to be included but there was no calculation mechanism.

The experiment found the flowchart approach does not generally have high resource requirements, requiring only simple and cheap software and the time for the investigator and participants to discuss options and plans. However, for more complex projects involving multiple parties such as the tool room in this experiment, the time resource use can be high due to data gathering, meetings and exchange of information through email. The method was flexible to be applied to ETO products using a template although this was not tested. Finally, the flowchart was found to be highly suitable for the early stage of planning as it was constructed by a small team with some basic information about the current process and ideas of possible improvements. It could be used as a preliminary stage in a more complex approach.

Table 22: Strengths and weaknesses of Flowchart approaches against the six criteria.

Flowchart			
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	3	-	Large number of meetings and communications
Usable	4	Easy to understand	Knowledge of subject required, lack of guidance on how to implement, explanation required
Non-Financial	1	-	Difficult to compare
Resources	7	Simple and cheap software	Requires group participation
ETO	9	Flexible structure, template could be used	-
Early stage	9	Only basic data needed	-

4.2.4 Consultancy/Tools for cost and time calculation

Literature had revealed some structured approaches to automation specification that were categorised as consultation or cost and time calculation approaches due to their reliance on discussions with customers and knowledge of consultants. The aim of these experiments was to test approaches for cost and time calculation, and evaluate them against the criteria for an approach. This was done by developing tools to assist sales engineers complete the process of specifying and quoting new automated production systems and trialling them in a real automation business. These tools were informed partly by literature and in part through observation and questioning of sales engineers and the author being immersed in the current processes. Conversations with sales engineers identified areas where their tasks were time consuming such as finding the costs of components, or relied on guesswork, for example cycle time estimation. Rather than developing a complete new procedure, which would have met high resistance due to resistance to change, elements of the current process were isolated and improved using relatively simple tools.

As part of a consultation method, the author designed an online automation assessment (Figure 6) that can be used as a sales tool enabling generation of leads to gain new customers and new projects for existing customers. The tool is implemented as an online form that guides the customer through a number of questions in a semi-interactive manner. The aim is to collect the prospective customers contact details and information on the type of automation required. The questions are also designed to give an idea of the feasibility of the proposed automation in terms of complexity and financial benefit. This data allows a sales engineer to follow up with further questions in an informed way. Further development of the follow up framework is required to conduct the consultancy approach in a structured way.

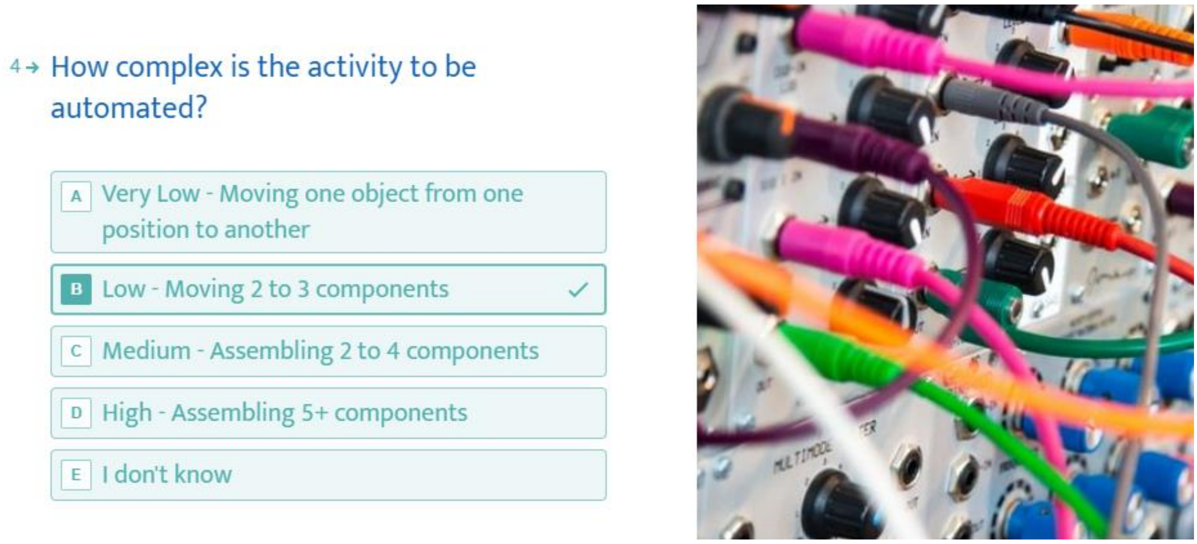


Figure 6: Question from the automation questionnaire.

One important factor when specifying any bespoke machinery for a customer is how much they can afford to pay. This is often restricted by being able to pay for itself in two years through either an increase in production or more often the reduction of staff required. This is a relatively simple calculation of number of staff repurposed multiplied by hourly cost, number of shifts per day and number of days per year. To make this calculation consistent and easy, an ROI calculator was included in the sales tool front page (Figure 7). This was tested by two sales engineers over several quotations and found to help by giving a price ceiling below which projects would be more likely to be accepted by customers.

Some useful calculation tools to make initial quoting easier			
Enter numbers in light grey boxes			
Get results from yellow boxes			

Return on Investment Calculator		Defaults	
Employee full cost per hour	16.9	16.9	Based on ONS statistics for Manufacturing in food and beverages 2019
Hours per shift	8	8	
Workers per shift	1	1	
Shifts per day	1	1	
Operating days per week	5	5	
Operating weeks per year	50	50	
Years to return investment	2	2	
Total return on investment	£67,600.00		

Previous Job Lookup					
Job Description Lookup	Job Number	Quote	Total	Material	Labour
Pallet conveyor infeed	21658	Q12017b	£17,000.00	£12,300.00	£4,700.00

Figure 7: Front page of sales assistance tool Excel spreadsheet including return on investment calculator and a previous job lookup table.

Another method used by sales engineers when attempting to calculate proposed costs for a new machine was to consult similar projects completed in the past. This not only helps by checking the overall price is reasonable but costs of individual components can be copied to the new quotation. However, the past quotes were all in folders organised by year and ascending quote number with a short description in their name, which made searching for similar projects a time consuming process. An attempt was made to overcome this by putting all the projects in a lookup table and providing a tool to choose from a dropdown menu of the job descriptions (Figure 7). This provided the job number and quote number for further investigation of components along with the total, material and labour costs for quick reference. Labour costs in particular are difficult to estimate and are mainly based on experience of similar projects. Further details of the consultancy experiments can be found in Appendix D.

Some aspects of the tools developed through this experiment contained elements of quantitative modelling and simulation such as the cycle time calculations, and database decision aids for example the past job lookup table. These themes have some overlap and can be used to complement each other. Where consultancy differs is in drawing these tools together and using them with knowledge and experience in consultations with customers. The sales assistance spreadsheet was used on several real automation projects and helped to calculate the cycle time and safety factors. It was found to be too basic to be useful in calculating costs as each project is almost completely different. An idea from one of the sales engineers, which could be implemented in the future, was creating a list of standard components with prices. This would include parts that are found on most machines such as programmable logic controllers (PLCs), buttons and screens. Prices would not be for any particular brand, rounded up and kept current by adding a small percentage every year. The list could be quickly completed using prices from recent projects. However, this tool could also have been created in the DDA theme again showing overlap between the two approaches.

The strengths and weaknesses of the consultancy or tools for cost and time calculation theme for each criterion are presented in Table 23. Calculation tools struggled with rapid application due to the large number of meetings and communications required between stakeholders. This also meant high resource use of highly skilled worker time. The theme was also not very useable by managers due to the need to have broad and detailed knowledge of automated production machinery to be able to produce accurate specifications. It is excellent at considering not just the financial costs and benefits as these can be discussed and voted upon during meetings although this was not tested here. Consultancy is useful for ETO products as the process is flexible and does not rely on processes that are specialised to one product.

Finally, this theme is useable at the early stage of planning as the process begins with an aim or customer need and draws in the required information which is used to make decisions by comparing options often in collaboration with the customer and other stakeholders such as mechanical or controls engineers.

Table 23: Strengths and weaknesses of Consultancy/tools for cost and time calculation against the six criteria.

		Consultancy/tools for cost and time calculation	
Criteria	**Score**	**Strengths**	**Weaknesses**
Rapid	4	Calculation performed by spreadsheet	Large number of meetings and communications required
Usable	3	Simple tools, graphical interface	Broad and detailed knowledge of automation required
Non-Financial	8	Can be discussed and voted on, safety calculations, robot selection criteria	Some tools do not address
Resources	6	Tools using spreadsheets are cheap and can be completed by a single engineer	Time of highly skilled workers
ETO	7	Process is flexible and not specific to one product, tools developed specifically for ETO	Differences between products can be so great that the tools are not usable
Early stage	7	Involves all parties from start and draws in information	Accurate information required

4.3 Summary

The main results from the experiments and literature review are summarised below in Table 24. The next Chapter goes on to discuss these results in detail with Figures and compare them with the ideas of other researchers encountered through the literature review in Chapter 2.

Table 24: Results of experiments and literature review.

Number	Result	Figure
1	Database decision aids had a high total preference proportion (PP) in both literature and experimental AHP analysis using the six criteria	Figure 27
2	QM&S had the lowest PP in literature and was also low in the experiments but not the lowest	Figure 27

3	Flowchart had the largest difference in PP between literature and experiment, having the highest PP in literature but the lowest PP in the experiments	Figure 27
4	Consultancy had a higher overall PP in the experiment than in literature	Figure 27
5	QM&S had the highest PP of all the themes for rapid application in literature and experiment	Figure 28
6	Consultancy had the lowest PP for rapid application in literature and the PP in the experiment was also low but increased slightly	Figure 28
7	Flowchart had a much lower PP for rapid application in the experiment than in the literature	Figure 28
8	DDA had a similar PP for rapid application in literature and the experiment	Figure 28
9	Flowchart had the highest PP for 'usable by managers with technical knowledge' in literature but had a much lower PP in the experiment	Figure 29
10	QM&S had a very low PP for *'usable by managers with technical knowledge'* in literature but had the joint highest PP in the experiment	Figure 29
11	DDA had a high PP for *'usable by managers with technical knowledge'* in both literature and the experiment	Figure 29
12	Consultancy had a low PP for 'usable by managers with technical knowledge' in both literature and experiment	Figure 29
13	DDA and Consultancy themes had the highest PP for 'considers not just the financial costs and benefits' in both literature and the experiments	Figure 30
14	QM&S had the lowest PP for *'considers not just the financial costs and benefits'* in both the literature and the experiments	Figure 30
15	Flowchart had a lower PP for *'considers not just the financial costs and benefits'* in the experiment than in literature	Figure 30
16	QM&S had a high PP for the criteria *'for small business/resource use'* in literature but was much lower in the experiment	Figure 31
17	DDA had the lowest PP for the criterion *'for small business/resource use'* in literature but was higher in the experiment	Figure 31
18	Flowchart and Consultancy had a high PP for the criterion *'for small business/resource use'* both in literature and the experiment	Figure 31
19	Flowchart and consultancy had the highest PP in both literature and the experiment for the criteria *'for ETO products'*	Figure 32
20	QM&S and DDA had the lowest PP in both literature and experiment for the criteria *'for ETO products'*	Figure 32
21	QM&S had the highest PP in literature but the lowest PP in the experiment for the criteria *'usable at the early stage of planning'*	Figure 33
22	Flowchart had the highest PP in the experiment for the criteria *'usable at the early stage of planning'*	Figure 33
23	DDA and Consultancy themes had a similar PP in literature and experiment for the criteria *'usable at the early stage of planning'*	Figure 33
24	The most successful experiment in practical terms was in the consultancy theme. Some of the developed tools were used on actual projects to improve accuracy of cycle time and safety estimates. However, the results of the AHP analysis suggest that DDA would be the most useful theme when all criteria are considered	Figure 33
25	The experimental results disagreed with the literature on the 'usable by managers with technical knowledge' and 'usable at the early stage of planning' criteria for the QM&S theme	Figure 34

26	The preference proportions for each criteria in the experiments generally confirmed the claims of other researchers for the DDA theme, except for its application to ETO products	Figure 35
27	The preference proportions in the experiments were higher for three criteria and lower for the remaining three than those from literature for the flowchart theme, disagreeing the claims of other researchers	Figure 36
28	The preference proportions from the experiments and literature overlap well for the consultancy theme, supporting the claims of other researchers	Figure 37

5 Discussion

5.1 Introduction

This Chapter attempts to answer the research questions by discussing the results from Chapter 4 and comparing them with existing literature reviewed in Chapter 2. The primary research question, *“how can an approach specify automation solutions?”* was addressed by examining existing research to identify themes and then experimenting with approaches. The relative merits of the four themes discovered were distilled through AHP to aid analysis and the results of the experiments compared with those of other researchers.

The second question, *“which criteria are important in an approach to specify automation solutions?”* was also investigated through existing sources. As described in Section 4.3.1 of the Results Chapter the relative importance of the criteria was calculated using analytical hierarchy process based on the number of high quality research papers explicitly mentioning them.

The third question, *“how well does existing literature meet the identified criteria?”* was answered by comparing between themes in existing research and against the results of experiments. These are presented in a series of bar charts showing the relative preference proportion for each criterion and radar charts to compare the relative benefits of each theme across the criteria.

This Chapter consists of firstly the analytical hierarchy analysis of the results in Section 5.2 followed by a brief discussion of the criteria that bound the study in Section 5.3 and a section for each result (5.4.1 to 5.4.29), in which the main points drawn from literature and supported or contradicted by empirical experimentation are discussed and the relative strengths and weaknesses of the four themes are compared. Finally, Section 5.5 is a summary of the most interesting results.

5.2 Analysis of results

5.2.1 Criteria

Analytical hierarchy process (AHP), was used to assess the four themes against the six criteria. For an explanation of AHP, see Chapter 3 Research methodology, Section 3.5.3 Analytical hierarchy process. The relation between the result at the top, the criteria on the next level and the themes beneath is graphically presented in the tree diagram in Figure 8. The proportion priority for each criteria was calculated through pairwise comparison based on the number of papers (Table 8) and is shown in Table 25. When these comparisons are entered into an AHP matrix, it yields the data in Table 26 and these are then normalised in Table 27.

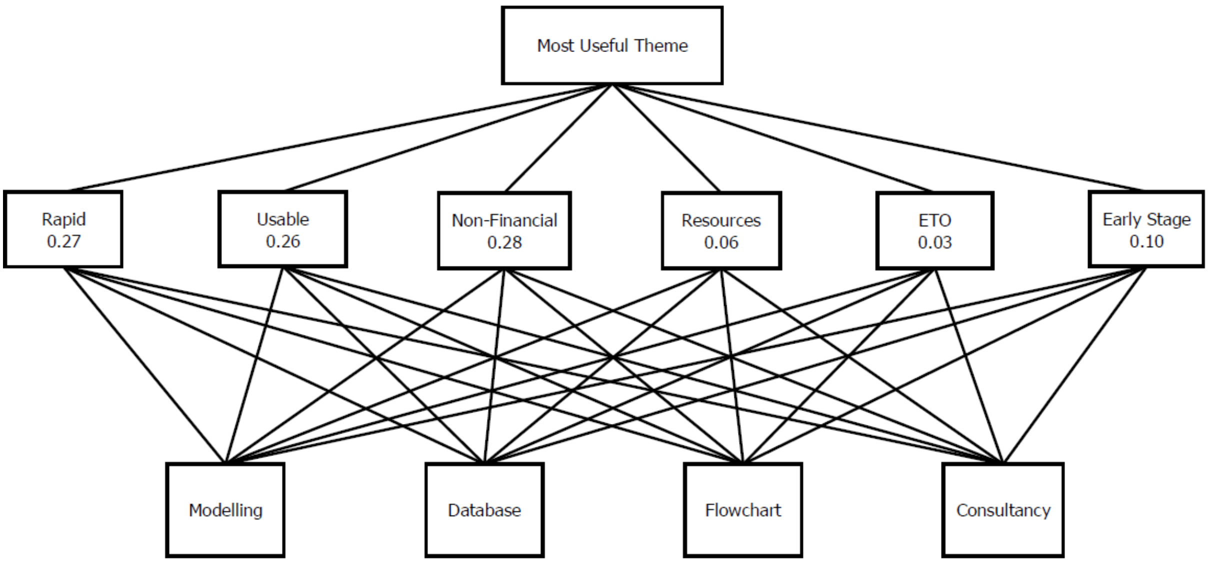


Figure 8: Analytical Hierarchy Process tree showing the relative priority of each criterion and the relations between themes, criteria and the overall priority that indicates the most useful theme.

Table 25: Criteria evaluated pairwise with reasons for each choice.

Criteria evaluated pairwise				Reasons
Rapid	1	Usable	1	Equal with 13 papers each
Rapid	1	Non-Financial	1	Equal with 13 papers each
Rapid	4	Resources	1	Rapid with 13 papers is moderately to strongly important compared with resources with 5 papers
Rapid	8	ETO	1	Rapid with 13 papers is very to extremely important compared with ETO with 3 papers
Rapid	3	Early stage	1	Rapid with 13 papers is moderately important compared with early stage with 8 papers
Usable	1	Non-Financial	1	Equal with 13 papers each
Usable	3	Resources	1	Usable with 13 papers is moderately more important than resources with 5 papers
Usable	8	ETO	1	Usable with 13 papers is very strongly to extremely more important than ETO with 3 papers
Usable	3	Early stage	1	Usable with 13 papers is moderately more important than early stage with 8 papers
Non-Financial	5	Resources	1	Non-financial with 13 papers is strongly more important than resources with 5 papers
Non-Financial	8	ETO	1	Non-financial with 13 papers is very to extremely more important than ETO with 3 papers
Non-Financial	3	Early stage	1	Non-financial with 13 papers is moderately more important than early stage with 8 papers
Resources	2	ETO	1	Resources with 5 papers is slightly to moderately more important than ETO with 3 papers
Resources	1	Early stage	2	Early stage with 8 papers is slightly to moderately more important than resources with 5 papers
ETO	1	Early stage	3	Early stage with 8 papers is moderately more important than ETO with 3 papers

Table 26: Analytical Hierarchy Process matrix of the results from the pairwise comparisons in Table 25.

AHP Matrix						
	Rapid	**Usable**	**Non-Financial**	**Resources**	**ETO**	**Early stage**
Rapid	1.00	1.00	1.00	4.00	8.00	3.00
Usable	1.00	1.00	1.00	3.00	8.00	3.00
Non-Financial	1.00	1.00	1.00	5.00	8.00	3.00
Resources	0.25	0.33	0.20	1.00	2.00	0.50
ETO	0.13	0.13	0.13	0.50	1.00	0.33
Early stage	0.33	0.33	0.33	2.00	3.00	1.00
Total	3.71	3.79	3.66	15.50	30.00	10.83

Table 27: Normalised Analytical Hierarchy Process matrix produced by dividing the values in Table 26 by the total of each column.

Normalised AHP Matrix							
	Rapid	**Usable**	**Non-Financial**	**Resources**	**ETO**	**Early stage**	**Priority**
Rapid	0.27	0.26	0.27	0.26	0.27	0.28	0.27
Usable	0.27	0.26	0.27	0.19	0.27	0.28	0.26
Non-Financial	0.27	0.26	0.27	0.32	0.27	0.28	0.28
Resources	0.07	0.09	0.05	0.06	0.07	0.05	0.06
ETO	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Early stage	0.09	0.09	0.09	0.13	0.10	0.09	0.10
Check Sum	1	1	1	1	1	1	1.00

The priority column on the right of Table 27 is the relative proportion importance of each criterion and for clarity these proportions have been presented graphically in Figure 9. The three criteria *non-financial* [consider not just the financial costs and benefits] (28%), *rapid* [application] (27%), and *usable* [by managers with technical knowledge] (26%) have the highest importance proportions. The lowest importance is *ETO* with 3%, closely followed by [for small business/]*resources* with 6%, and [usable at the] *early stage* with 10%. These proportions from AHP are not the same as those that could be simply calculated by dividing the number of papers in each category by the total number of papers in the sub-group.

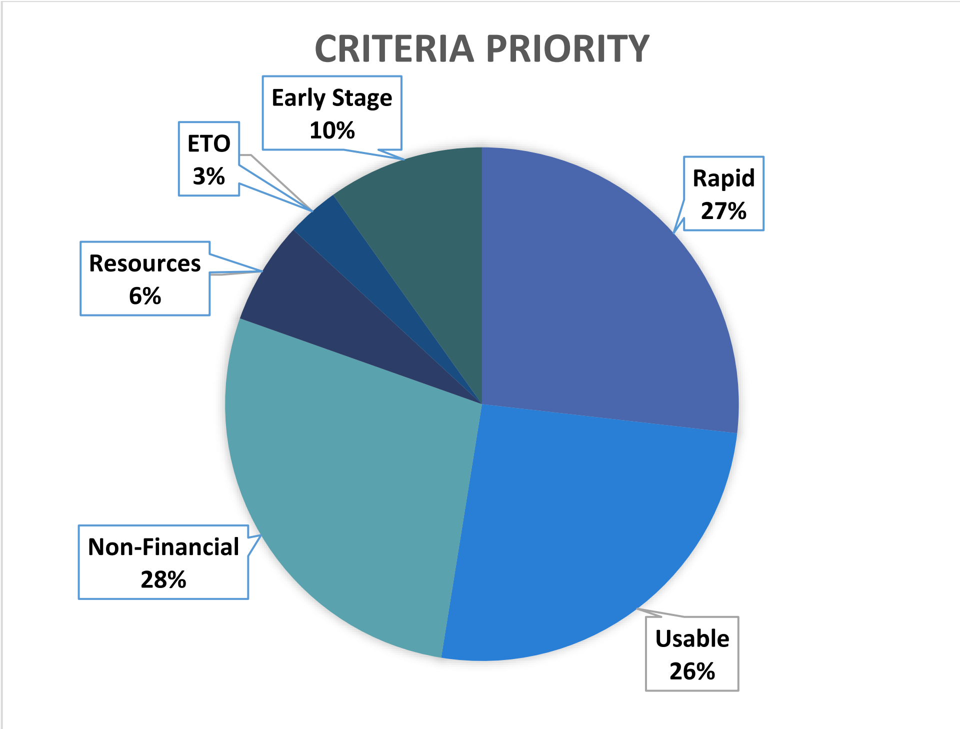


Figure 9: Relative priority of each criteria as calculated through Analytical Hierarchy Process.

The consistency ratio (Table 28) for the pairwise comparisons of the criteria was 1.00%, which gives a high confidence that the comparisons are logically consistent.

Table 28: Consistency ratio for AHP calculation of criteria priority.

Consistency Ratio	
Max Eigen =	6.04
CI =	0.01
RI=	1.41
Consistency Ratio =	1.00

5.2.2 Experimental AHP

After the priorities of the criteria had been created a pairwise comparison of the four identified themes was conducted for each criterion. This was informed by the experiments and comments from managers involved in the process. The calculations for Rapid Application are reproduced here (Table 29, Table 30, Table 31 and Table 32) and every table is presented in Appendix C.

Table 29: Pairwise Comparison of Themes for Rapid Application from Experiment Results.

Pairwise Comparison of Themes for Rapid Application from Experiment Results				
Themes evaluated pairwise				**Reasons**
QM&S	9	**DDA**	6	Both use computers to speed up use
QM&S	9	**Flowchart**	3	Flowchart required multiple meetings and communication over email
QM&S	9	**Consultancy**	4	Consultancy required multiple meetings and communication over email
DDA	6	**Flowchart**	3	Flowchart required multiple meetings and communication over email
DDA	6	**Consultancy**	4	Consultancy required multiple meetings and communication over email
Flowchart	3	**Consultancy**	4	Both required multiple meetings

Table 30: Analytical Hierarchy Process matrix of the results from the pairwise comparisons in Table 29.

AHP Matrix for Rapid Application					
	QM&S	**DDA**	**Flowchart**	**Consultancy**	**Eigenvector**
QM&S	1.00	1.50	3.00	2.25	0.41
DDA	0.67	1.00	2.00	1.50	0.27
Flowchart	0.33	0.50	1.00	0.75	0.14
Consultancy	0.44	0.67	1.33	1.00	0.18
Sum	2.44	3.67	7.33	5.50	1.00

Table 31: Normalised AHP Matrix for Rapid Application.

Normalised AHP Matrix for Rapid Application						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Preference**	**Global Preference**
QM&S	0.409	0.409	0.409	0.409	0.409	0.110
DDA	0.273	0.273	0.273	0.273	0.273	0.073
Flowchart	0.136	0.136	0.136	0.136	0.136	0.037
Consultancy	0.182	0.182	0.182	0.182	0.182	0.049

The local preferences in Table 31 and graphically represented in Figure 10 show the relative success of each theme for the Rapid Application criteria. QM&S was the quickest, closely followed by DDA. The calculated consistency ratio of 0.00% (Table 32) gives an indication that the ranking choices were logically consistent.

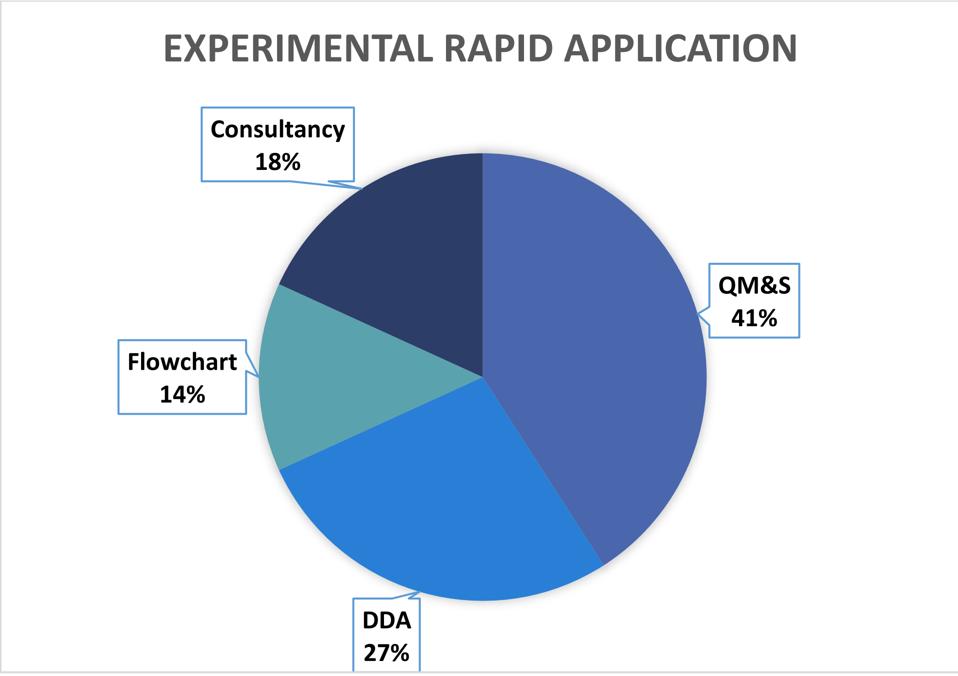


Figure 10: Relative local preferences for each theme against the criterion "Rapid application" from the experiments.

Table 32: Rapid application consistency ratio.

Rapid Application Consistency Ratio	
Criteria Priority =	0.27
Max Eigen =	4.00
CI =	0.00
RI=	0.90
Consistency Ratio =	0.00

The other criteria were used to assess the themes in the same way and yielded the graphs below (Figure 11, Figure 12, Figure 13, Figure 14, and Figure 15).

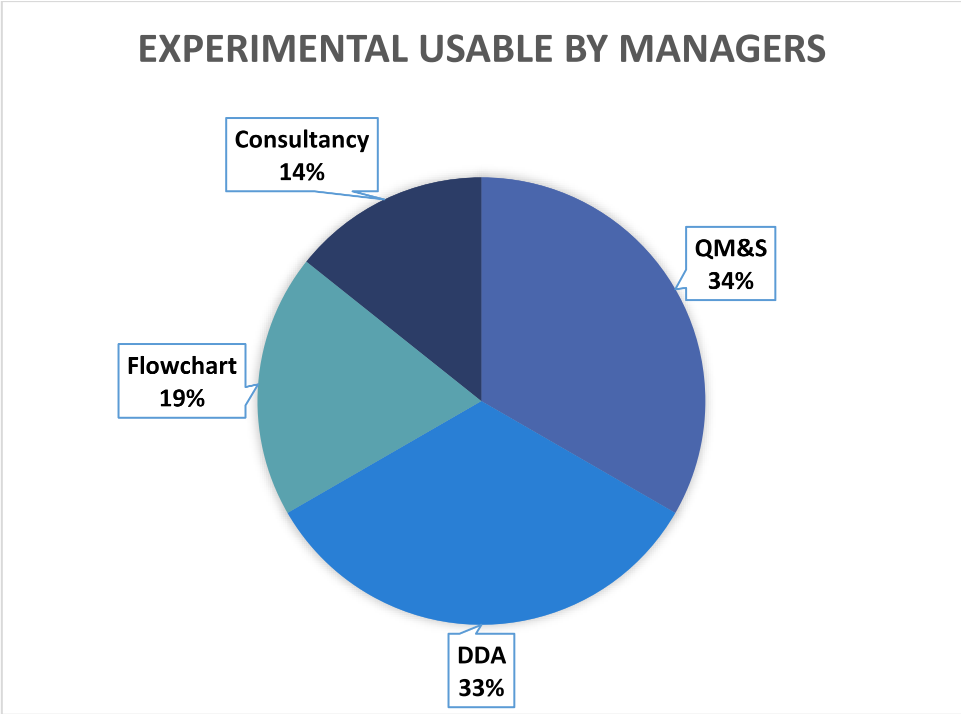


Figure 11: Relative local preferences for each theme against the criterion "Usable by managers" from the experiments.

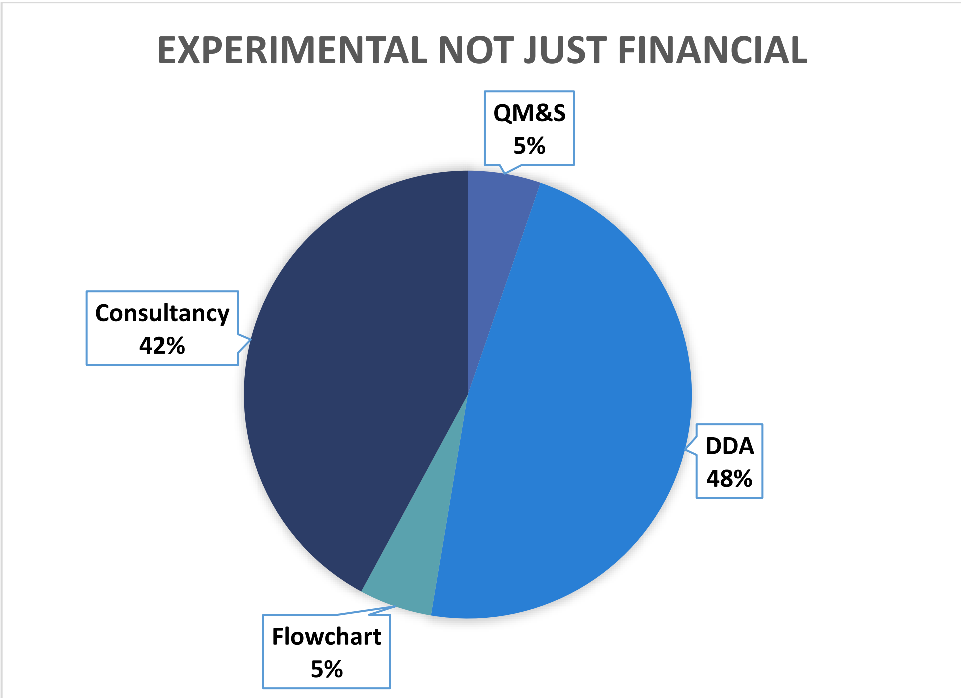


Figure 12: Relative local preferences for each theme against the criterion "Not just financial" from the experiments.

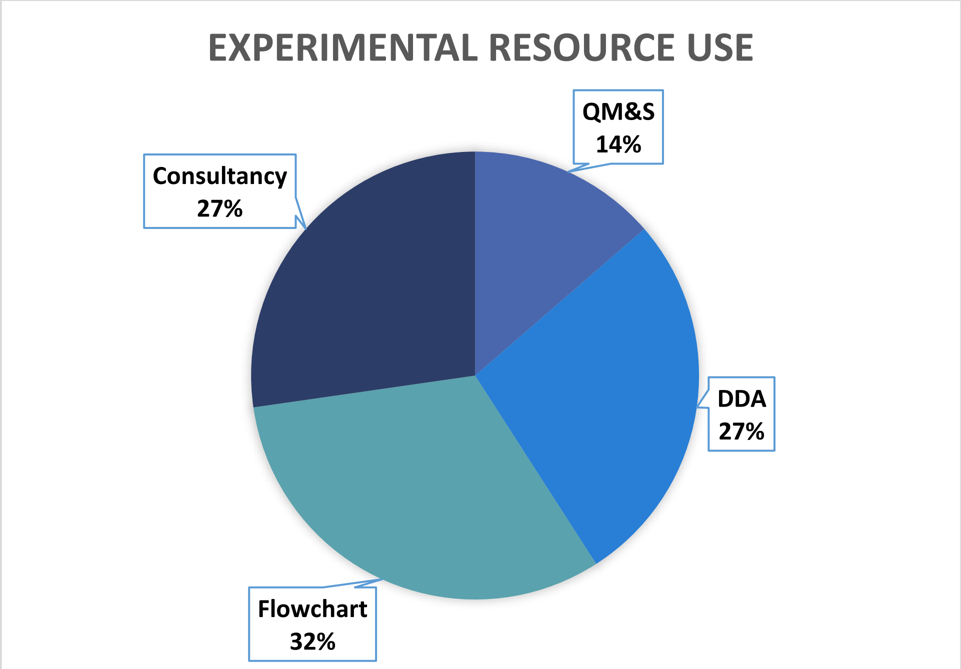


Figure 13: Relative local preferences for each theme against the criterion "Resource Use" from the experiments.

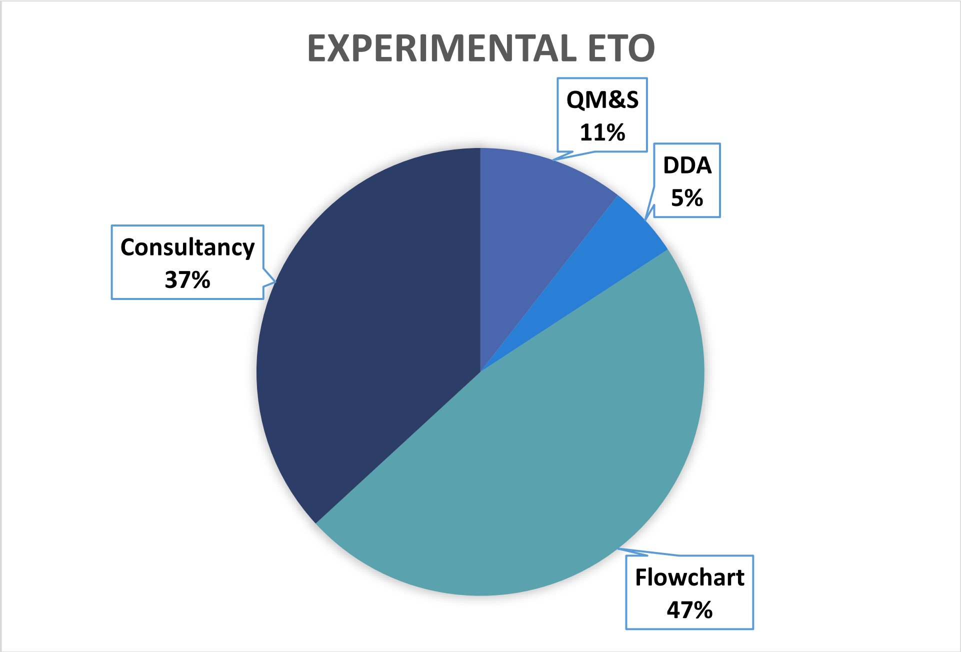


Figure 14: Relative local preferences for each theme against the criterion "For ETO products" from the experiments.

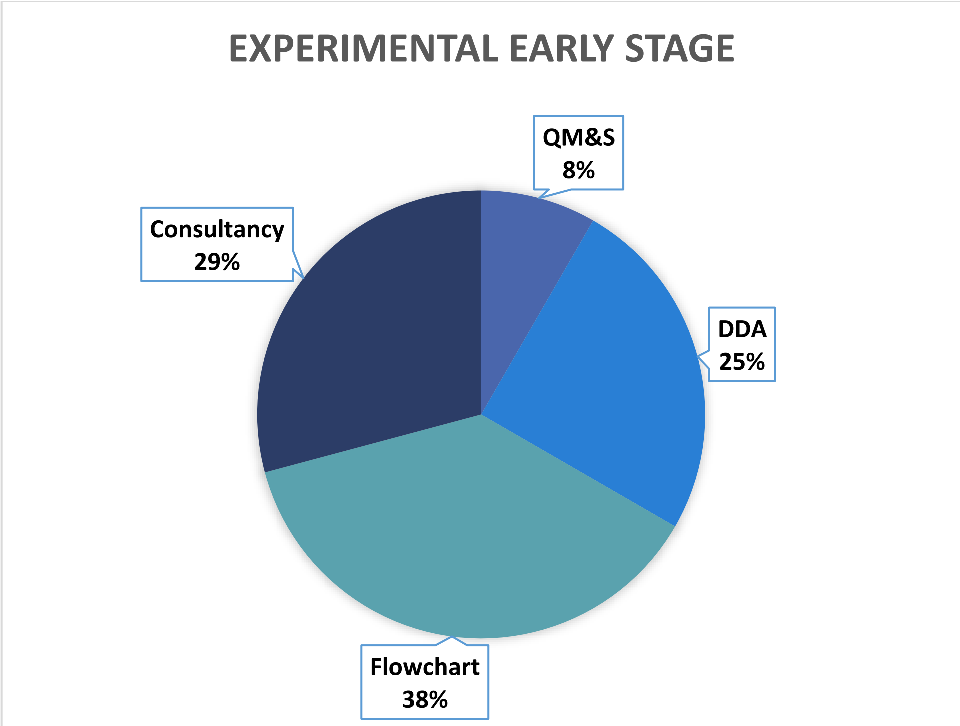


Figure 15: Relative local preferences for each theme against the criterion "Early Stage" from the experiments.

The next step is to put all of these global priorities into Table 33 and sum the rows to calculate the overall proportions (total preference) for each theme. The relative global proportions for each theme and criteria are shown in Figure 16. This shows not only the preference of each theme against each criteria but also the relative priority of each criteria.

Table 33: Analytical Hierarchy Process matrix of themes against criteria for the experiments.

	Rapid application	Usable by managers with technical knowledge	Considers not just the financial costs	Resource use	For ETO products	Usable at the early stage of planning	Total Preference
QM&S	0.110	0.086	0.015	0.009	0.003	0.008	0.231
DDA	0.073	0.086	0.132	0.018	0.002	0.025	0.335
Flowchart	0.037	0.049	0.015	0.021	0.016	0.037	0.173
Consultancy	0.049	0.037	0.117	0.018	0.012	0.029	0.261

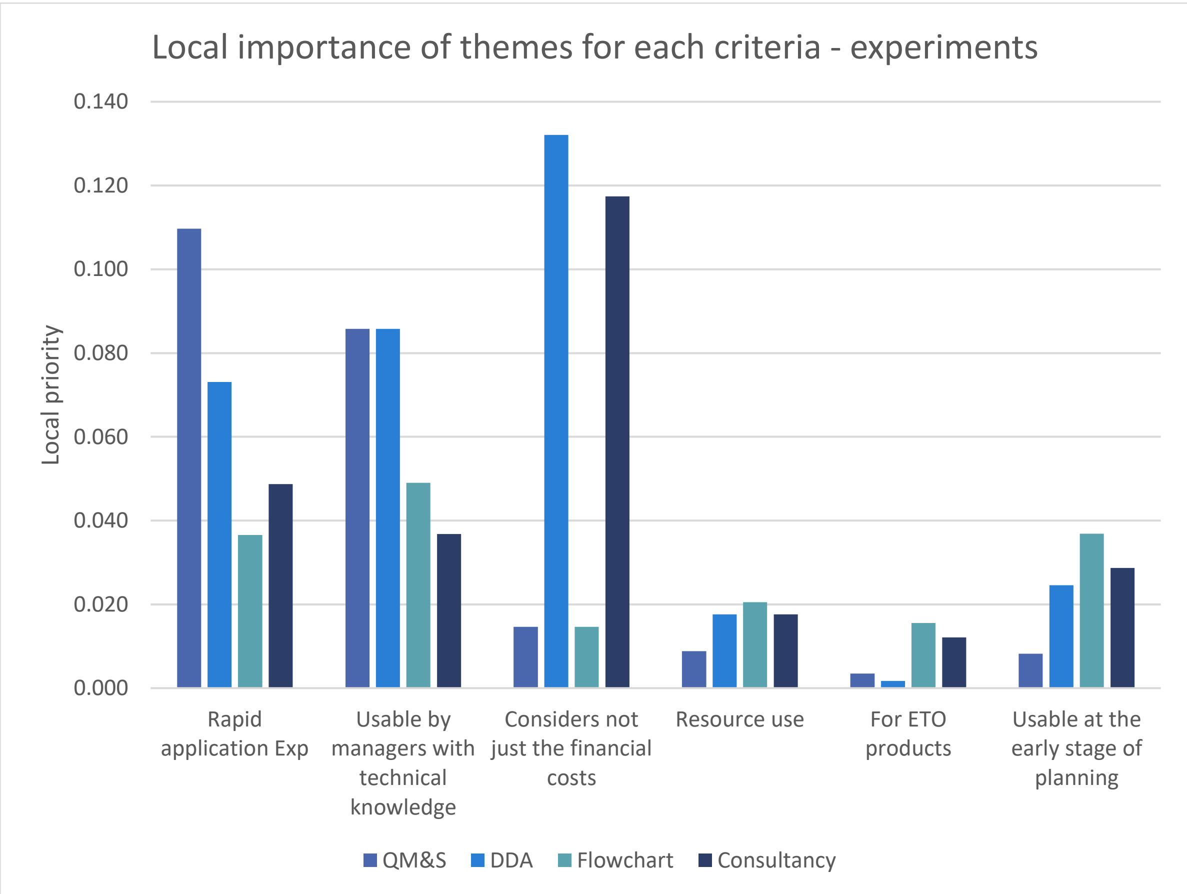


Figure 16: Bar graph of the local importance of each theme against each criteria for experimental results.

Figure 17 shows that DDA was the theme with the highest preference, closely followed by Consultancy and then QM&S. Flowchart was the theme with the lowest preference in this research.

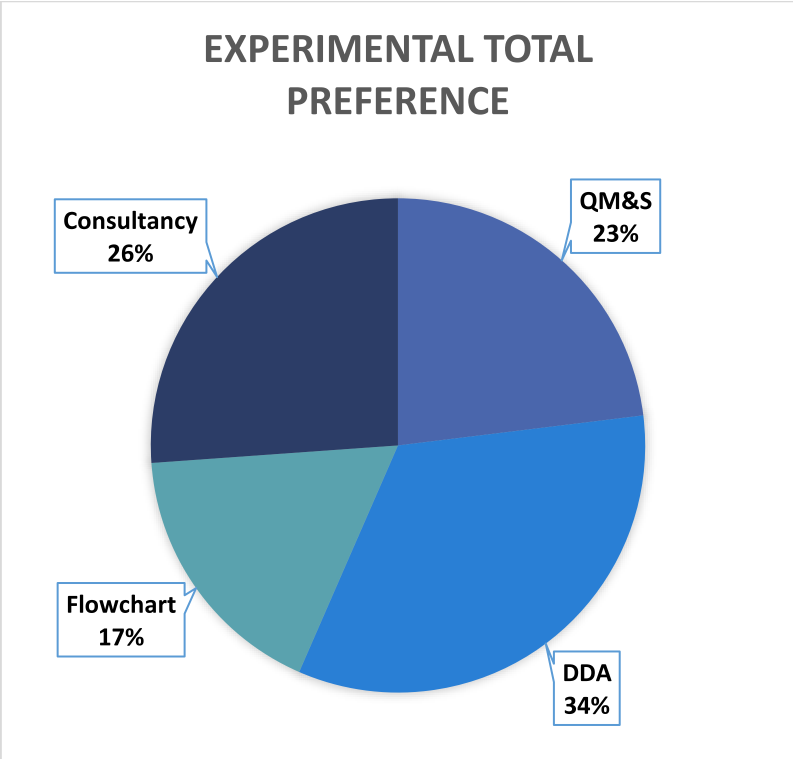


Figure 17: Chart of the proportion preference for each theme from the experiments.

5.2.3 Literature AHP

After the priorities of the criteria had been created a pairwise comparison of the four identified themes was conducted for each criterion. This was informed by the number of papers of each theme mentioning the criterion. The calculations for Rapid Application are reproduced here (Table 34, Table 35, Table 36) and every table is presented in Appendix C.

Table 34: Pairwise Comparison of Themes for Rapid Application from Literature.

Pairwise Comparison of Themes for Rapid Application from Literature				
Themes evaluated pairwise				**Reasons**
QM&S	1.125	**DDA**	1	Both use computers to speed up use
QM&S	1.125	**Flowchart**	1	Flowchart required multiple meetings and communication over email
QM&S	3	**Consultancy**	1	Consultancy required multiple meetings and communication over email
DDA	1	**Flowchart**	1	Flowchart required multiple meetings and communication over email
DDA	2.67	**Consultancy**	1	Consultancy required multiple meetings and communication over email
Flowchart	2.67	**Consultancy**	1	Both required multiple meetings

Table 35: AHP Matrix for Rapid Application from Literature.

AHP Matrix for Rapid Application from Literature					
	QM&S	**DDA**	**Flowchart**	**Consultancy**	**Eigenvector**
QM&S	1.00	1.13	1.13	3.00	0.32
DDA	0.89	1.00	1.00	2.67	0.29
Flowchart	0.89	1.00	1.00	2.67	0.29
Consultancy	0.33	0.38	0.38	1.00	0.11
Sum	3.11	3.50	3.50	9.33	1.00

Table 36: Normalised AHP Matrix for Rapid Application from Literature.

Normalised AHP Matrix for Rapid Application from Literature						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Preference**	**Global Preference**
QM&S	0.321	0.321	0.321	0.321	0.321	0.086
DDA	0.286	0.286	0.286	0.286	0.286	0.077
Flowchart	0.286	0.286	0.286	0.286	0.286	0.077
Consultancy	0.107	0.107	0.107	0.107	0.107	0.029

The local preferences in Table 36 and graphically represented in Figure 18 show the relative success of each theme for the Rapid Application criteria. QM&S was the quickest, closely followed by DDA. The calculated consistency ratio of 0.00% (Table 37) gives an indication that the ranking choices were logically consistent.

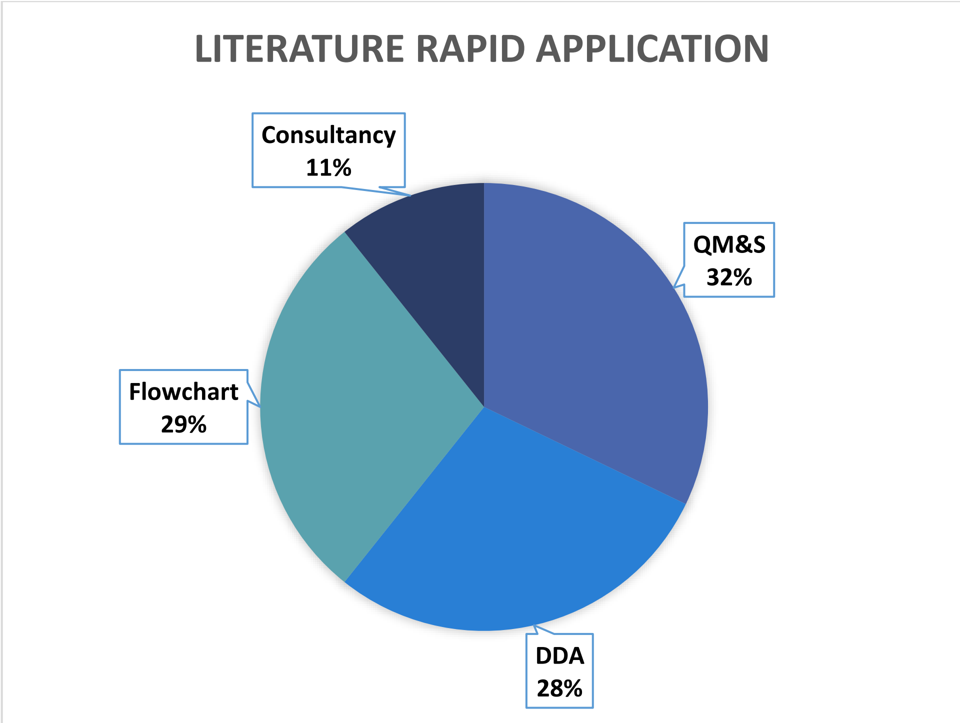


Figure 18: Relative local preferences for each theme against the criterion "Rapid application" from literature.

Table 37: Rapid Application Consistency Ratio.

Rapid Application Consistency Ratio	
Criteria Priority =	0.27
Max Eigen =	4.00
CI =	0.00
RI=	0.90
Consistency Ratio =	0.00

The other criteria were used to assess the themes in the same way and yielded the graphs below (Figure 19, Figure 20, Figure 21, Figure 22, and Figure 23).

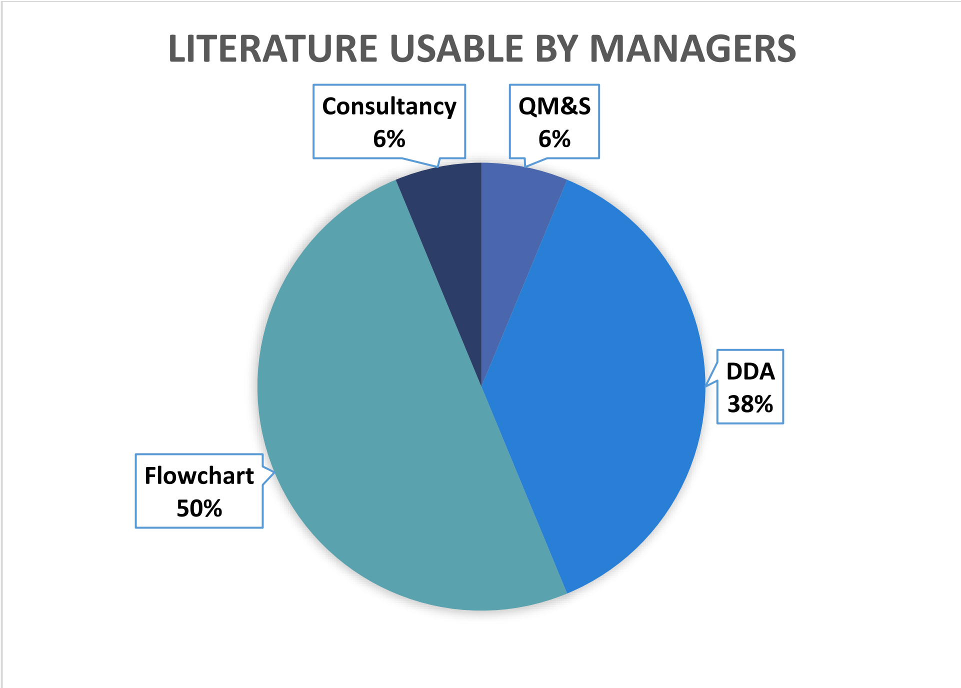


Figure 19: Relative local preferences for each theme against the criterion "Usable by managers" from literature.

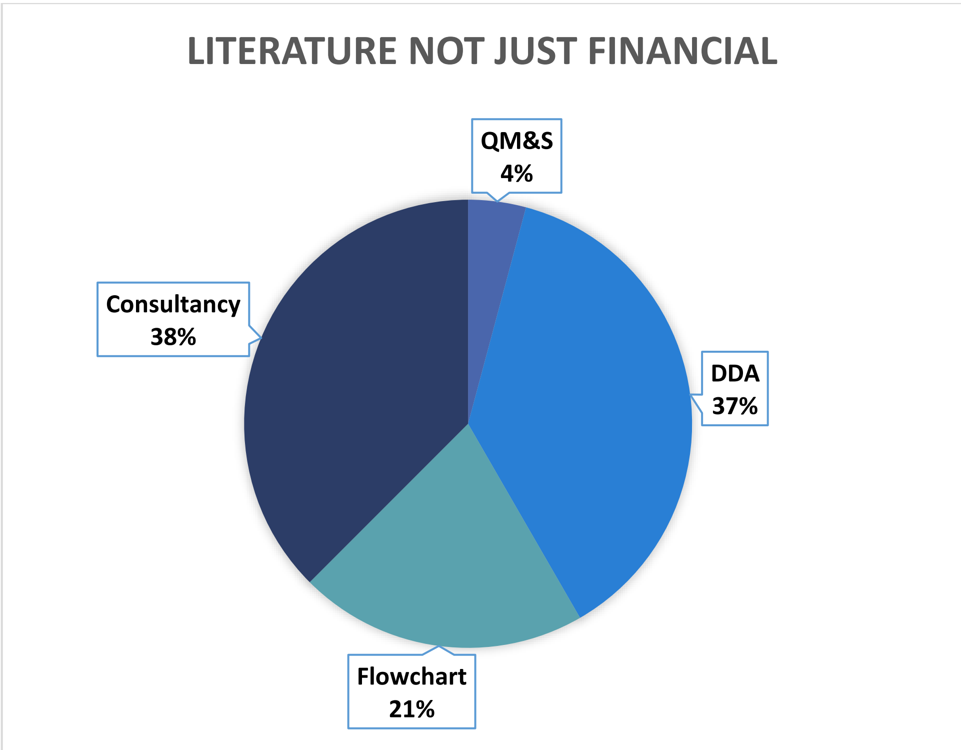


Figure 20: Relative local preferences for each theme against the criterion "Not just financial" from literature.

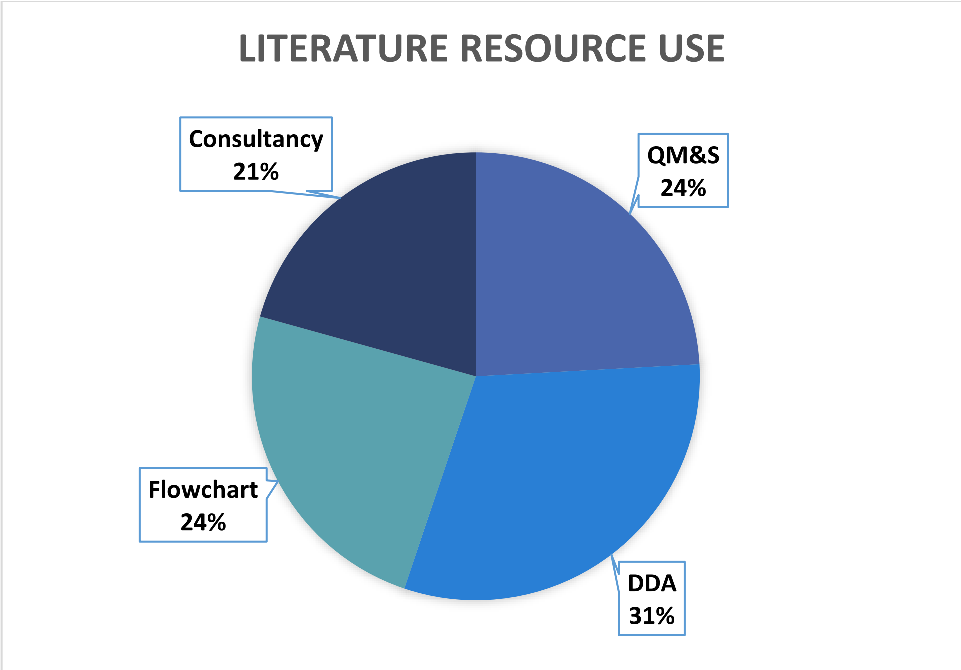


Figure 21: Relative local preferences for each theme against the criterion "Resource Use" from literature.

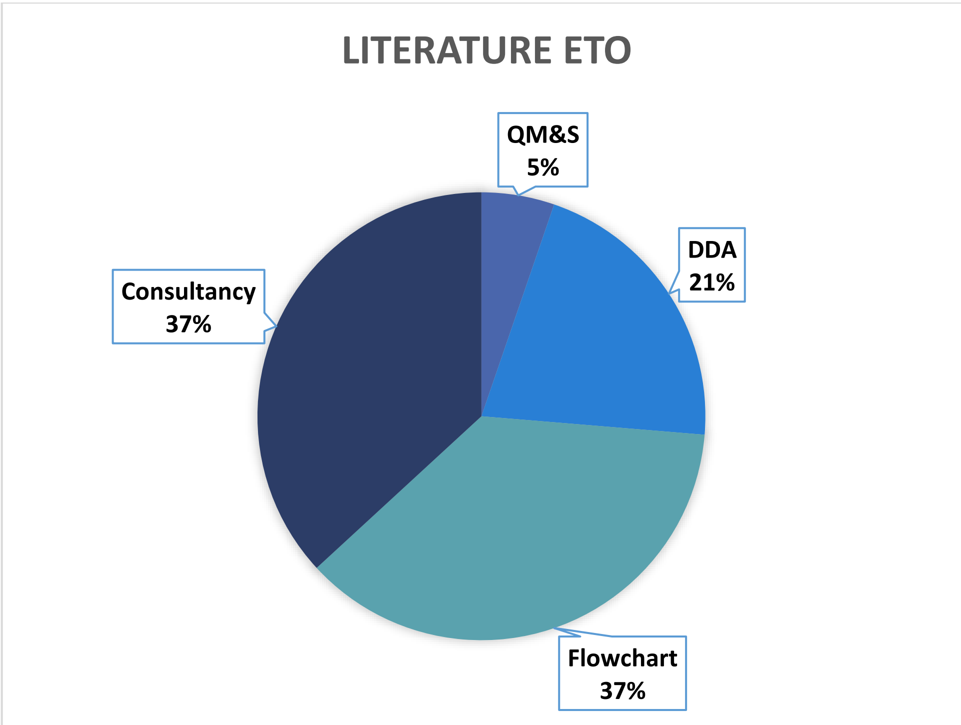


Figure 22: Relative local preferences for each theme against the criterion "For ETO products" from literature.

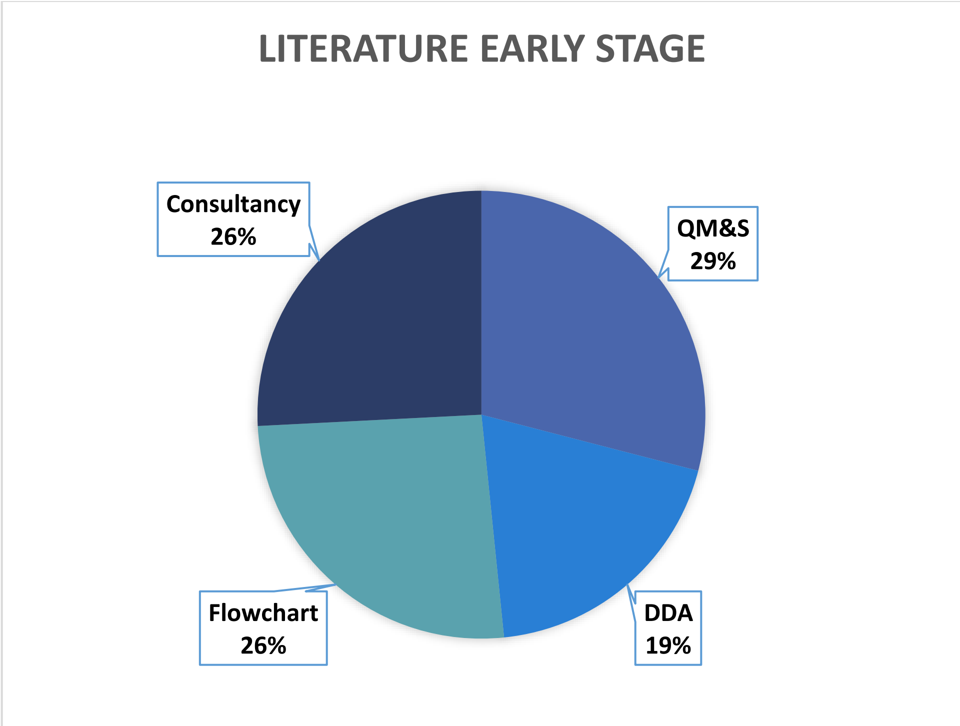


Figure 23: Relative local preferences for each theme against the criterion "Early Stage" from literature.

The next step is to put all of these global preferences into Table 38 and sum the rows to calculate the overall preference for each theme. The relative local proportions for each theme and criteria are shown in Figure 24. This shows not only the preference for each theme against each criteria but also the relative preference of each criteria. The total preference for each theme is also presented in Figure 25.

Table 38: Analytical Hierarchy Process matrix of themes against criteria for results from literature.

	Rapid application	Usable by managers with technical knowledge	Considers not just the financial costs	Resource use	For ETO products	Usable at the early stage of planning	Total Preference
QM&S	0.086	0.016	0.012	0.016	0.002	0.029	0.160
DDA	0.077	0.096	0.105	0.020	0.007	0.019	0.324
Flowchart	0.077	0.129	0.058	0.016	0.012	0.025	0.316
Consultancy	0.029	0.016	0.105	0.013	0.012	0.025	0.200

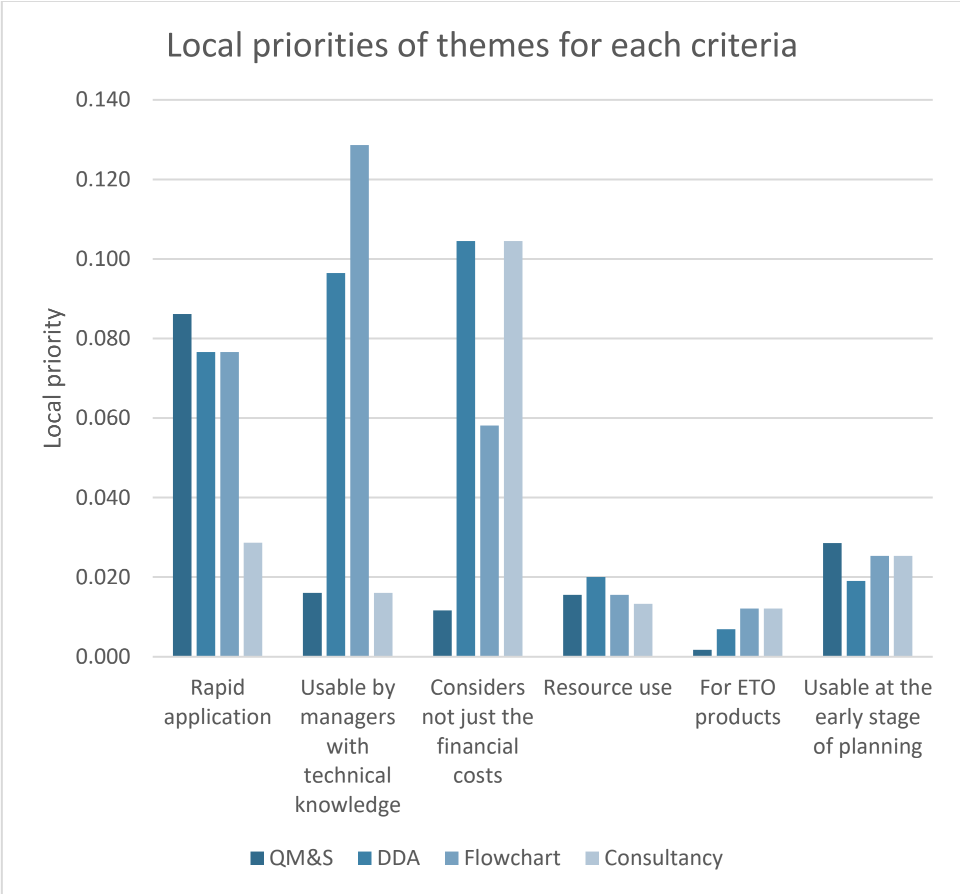


Figure 24: Bar graph of the local preference of each theme against each criteria from the literature review.

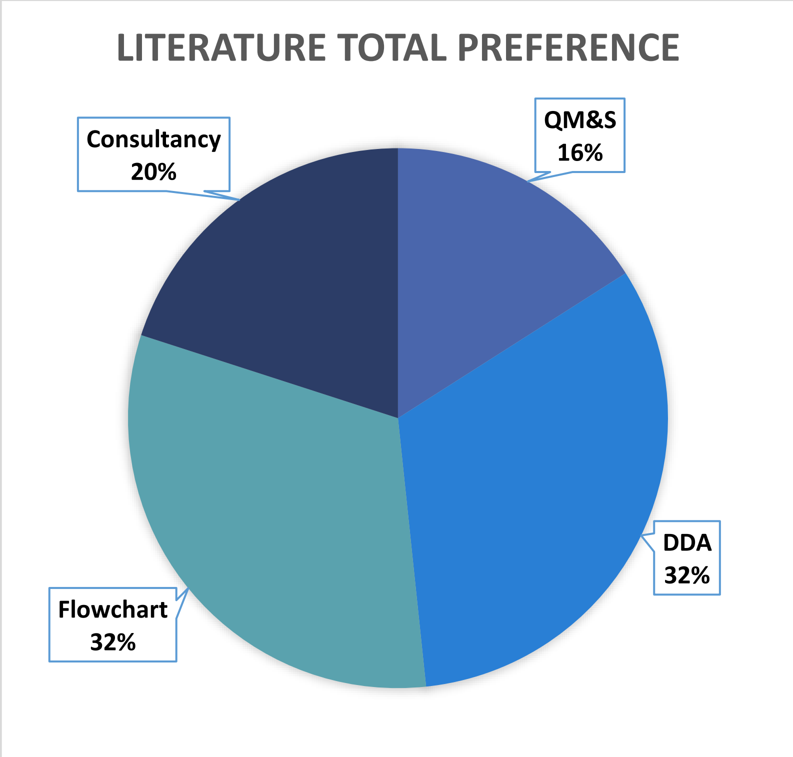


Figure 25: Chart of the proportion total preference for each theme from literature.

5.3 Criteria

As related in the Results Chapter Section 4.3.1, AHP was used to calculate the relative importance of the six criteria through counting the number of papers explicitly mentioning each criterion from Table 9 to aid in the pairwise comparisons shown in Table 16. This yielded the relative importance or priority shown in Figure 9. Due to the crude method of using frequency of occurrence to inform the pairwise comparisons of the AHP, the relative importance cannot be used quantitatively. For example, 'rapid application' cannot be said to be 1% more important than 'usable by managers with technical knowledge', but the ranking can inform the discussion. Certainly, these two criteria along with 'consider not just the financial costs and benefits' are equally important in an approach to specify automation. These assessments are purely from the literature so cannot be evaluated against experimental results in the same way that the themes were. As mentioned previously (Section 2.4.1 Introduction) we must be aware of the important caveats when comparing ideas based on the number of papers. These values were used to weight the local preference proportions of the themes for each criteria when calculating the overall preference proportion.

Some correlation exists between the broad to specific spectrum (Figure 1) and the priorities assigned to the criteria. This appears to mean that criteria on the broad end of the spectrum are more important. However, this could be due to the broader nature of these criteria and would represent the result of the caveats with using number of papers to rank ideas from literature. Most notably, researchers will research what they know and what is accessible or easy.

5.4 Discussion of results

5.4.1 Result 1 – DDA preferred overall

People preferred Database Decision Aids as revealed by the high total preference proportion in both literature and experimental AHP analysis using the six criteria. This can be observed in Figure 26. As with the criteria in Section 5.2, these cannot be assessed quantitatively, for example we cannot say that the DDA theme was 14% better than the consultancy theme in literature. However, the relative preference and ranking can be used to draw some useful conclusions. This result is dependent not only on the local preference proportions of the themes for each criterion but also on the relative priority of each of the criteria. This can be observed in Figure 27, which shows DDA had the highest preference in both literature and the experiment mainly because it scored highly in the three criteria with the highest priority; *'rapid application'*, *'usable by managers with technical knowledge'* and *'considers not just the financial costs and benefits'*. In reviewed literature Asawachatroj et al. (2012), Goh et al. (2020), Hamzeh et al. (2018), Ramis et al. (2015), Sambasivarao and Deshmukh (1997), Savoretti et al. (2017), supported DDA for these higher priority criteria and this was confirmed by the results of the experiments. This result requires us to separate use of the DDA, which once constructed would be fast and easy and require only basic knowledge of users, from the creation of the DDA that would be time consuming, complex and need thorough understanding of both DDAs and automation specification. The author focussed on the use of the DDA within a business as it could be purchased or DDA development could be carried out by external providers.

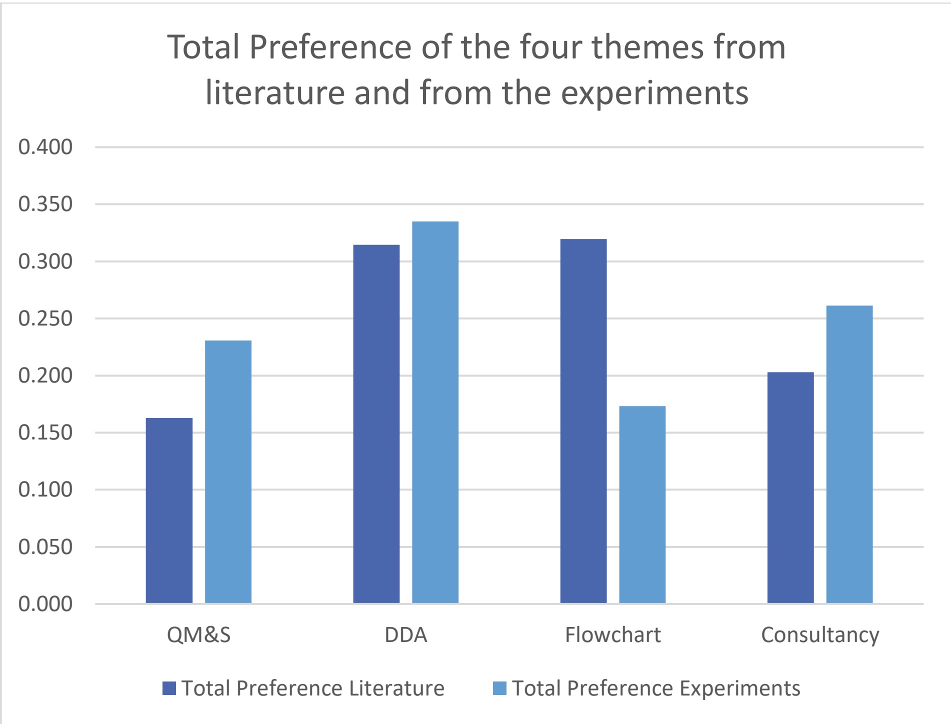


Figure 26: Overall preference proportion of the four themes from literature and the experiments calculated through AHP analysis.

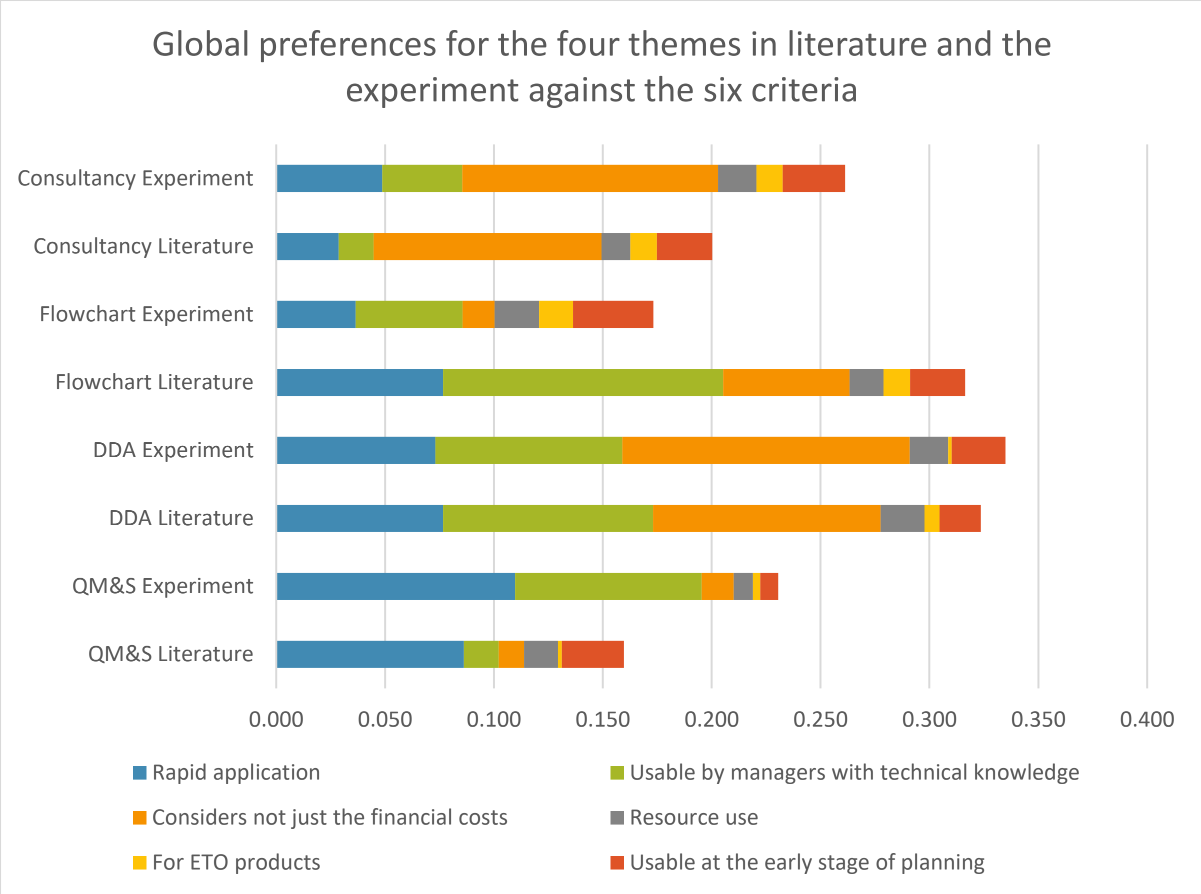


Figure 27: Global preferences for the four themes in literature and the experiment against the six criteria.

5.4.2 Result 2 – QM&S least preferred overall

QM&S had the lowest preference in literature and was also low in the experiments but not the lowest (Figure 26). By examining Figure 27, we can see the greater overall preference of the theme in the experiment was mainly due to the preference for the *'usable by managers with technical knowledge'* criterion being greater, which is discussed in detail in Section 5.3.10. The low preference in literature was partly due to criticism of the themes usability by managers from Fischer, Obst and Lee (2017), Kim and Lee (2013), Lechevalier et al. (2018), Long, Zeiler and Bertsche (2016), Ng, Urenda and Svensson (2007) and Wuest et al. (2016) but the experiment did not agree that QM&S tools were not useable by managers. This disagreement could be because the referenced authors did not develop their approaches to be easy to use but rather to provide detailed and accurate results, whereas the experimental QM&S was more focussed on ease of use.

Another reason for the low preference in literature was the themes' lack of the ability to consider non-financial costs and benefits claimed by Alfnes et al. (2016), Farooq and O'brien (2012 and 2015), Hamzeh et al. (2018), Lindstrom and Winroth (2010), Ordoobadi and Mulvaney (2001), Roy et al. (2017), Sambasivarao and Deshmukh (1997) and Thomassen et al. (2016). The experiment confirmed that the tools were not able to account for intangible factors as there was no way to quantify them for input to the model, and this is expanded in Section 5.3.14.

5.4.3 Result 3 – Flowchart had greatest difference in preference between literature and experiment

Flowchart had the largest difference in preference between literature and experiment, having a high preference in literature but the lowest preference in the experiments (Figure 27) due to much lesser preference for the three criteria with the highest priority. These are discussed in more detail in Results 7, 9, 15 and 29 with reference to literature, but as related in the Results Chapter Section 4.2.3 Flowchart modelling the experimental flowchart was found to be time consuming, required specialist knowledge and understanding, and did not consider costs and benefits whether financial or intangible. This contrasts with Ang (1999) and Rahman and Mo (2010) and (2012a) who found flowcharts provided rapid application, Fast-Berglund and Stahre (2013) and Erasmus et al. (2020), and Wehrmeister et al. (2014) who claimed usability of flowcharts, and De Felice, Petrillo and Zomparelli (2018b) who used flowcharts for costs and benefits other than financial. The disagreement with the results of these authors may be due to differences in the case environment, research methodology, or aims of their research.

5.4.4 Result 4 – Consultancy more preferred in experiment than literature overall

Consultancy had a higher overall preference proportion in the experiment than in literature (Figure 27) and this was again due to higher preference for the three criteria with high priorities. These are discussed further in Results 6, 12 and 13 with reference to the work of Thomassen, Sjøbakk and Alfnes (2014), Rother and Shook (1999), Thompson (1995), Baines (2014), Farooq and Obrien (2012 and 2015), Fast-Berglund and Stahre (2013), Larsen (1994), and Ordoobadi and Mulvaney (2001). However, this change is not as dramatic as that in result three and may not represent the experiment contradicting the literature. Due to the relative nature of AHP analysis, the increases for the consultancy theme are in part due to the decreases in preference proportion of other themes in particular the flowchart theme. This makes it problematic to draw conclusions from this result.

5.4.5 Result 5 – QM&S most preferred for rapid application

QM&S had the highest preference proportion of all the themes for *'rapid application'* in literature and the experiment as shown in Figure 28. QM&S was praised in literature for offering rapid application by Bradford (2000), Heilala, Helin and Montonen (2006), Shehabuddeen et al. (2006), Guschinskaya et al. (2011), Busogi et al. (2017), and Salmi et al. (2018) due to the use of computers to carry out complex calculations and the experimental results appear to support this. However, current methods were criticised for being slow by Salmi et al. (2015), and by Bokrantz et al. (2018) due to the highly detailed input data required and this was supported by the experiment, as data was scarce and inaccurate.

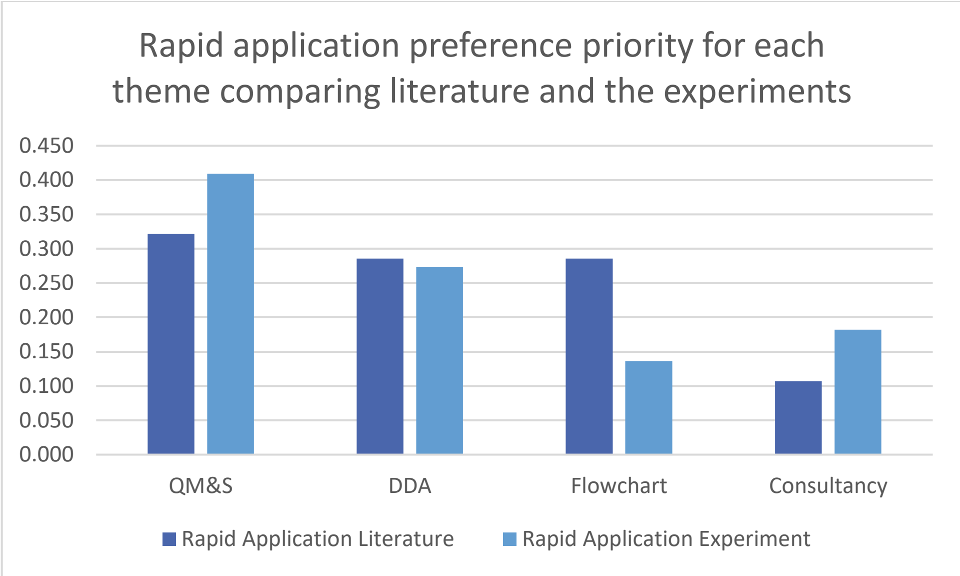


Figure 28: Preference priority of each theme for rapid application, comparing literature and the experiments.

The experiment carried out showed three main contributors to speed of application. Firstly, a large time investment was needed to develop the modelling software and user interface. However, this time investment was only needed once, unless the tool must be tailored for each new case, so it could be claimed not to affect the speed of application but would instead be relevant to the *'for small business/resources'* criterion. Secondly, the amount of time required to gather input data depended highly on the level of granularity or detail required. This is compounded by the availability of data and the form it is in, for example, a searchable database or hundreds of individual excel spreadsheets, which supports the arguments of Salmi et al. (2015) and Bokrantz et al. (2018) about data paucity. Thirdly, the amount of time to run the experimental simulation did not represent a large time investment, with the most complex model being simulated for two weeks of running time in less than ten minutes. This agrees with many of the researchers in this category confirming that QM&S is well suited to deliver rapid application and it can be claimed that the experimental evidence confirms the claims of other researchers that QM&S is the strongest theme for the rapid application criteria.

5.4.6 Result 6 – Consultancy least preferred for rapid application

Consultancy had the lowest preference proportion for *'rapid application'* in literature and the preference proportion in the experiment was also low but increased slightly (Figure 28). Consultancy approaches were criticised as time consuming by Thomassen, Sjøbakk and Alfnes (2014), and Rother and Shook (1999) noting that many loops, repeating steps, discussions and meetings were required. Stähr, Englisch and Lanza (2018) concurred and attempted to improve speed of application by only considering cost drivers that cause different configuration costs rather than doing full cost accounting for each configuration option. An experimental solution provided for the company followed a similar idea of simplification, using gathered data to construct a simple job lookup tool that provided the material and labour costs and the job number for further investigation (Figure 7). This was fast but extremely low detail and a tool providing more data but requiring more time could be an improvement. The authors' experimental tools to assist sales consultations were tested by giving them to the engineers and business development managers to use and recording their impressions and suggestions for improvement. A mix of sentiments were received ranging from generally positive that the tools could be useful to speed up workflows with some further development, to regarding them as a distraction and waste of time. This somewhat confirms the feeling in literature that rapid application is not a strength of the consultancy theme.

5.4.7 Result 7 – Experimental flowchart contradicts literature on rapid application

Flowchart had a much lower preference proportion for '*rapid application'* in the experiment than in the literature (Figure 298). Flowchart modelling with IDEF0 was claimed by Ang (1999) and Rahman and Mo (2010) and (2012a) to provide rapid application for specification of manufacturing systems. The former by integrating it in a software tool and the latter by using it not just to plan the manufacturing system but to plan the steps required in the specification process. IDEF0 was also used by Perera and Lyanage (2000) to give fast identification and selection of data for the simulation of manufacturing systems, though this is only one facet of the overall specification process. In the experiment conducted by the author, flowcharts were found to be relatively quick to construct and greatly sped up the transfer of complex information between different stakeholders, which agrees with the findings from Ang (1999), Perera and Lyanage (2000) and Rahman and Mo (2010) and (2012a). However, the necessity for input from multiple stakeholders that were experts in different facets of automation specification required several meetings and numerous emails to acquire which was a time consuming process. None of the papers in the literature review mentioned this and it could be inferred that they did not suffer this issue or did not include it in their findings, which seems more likely based on the author's experience. The four papers claiming flowcharts were beneficial for speeding up specification are contradicted by the findings of the experiment in this research as although the construction of the flowchart was reasonably fast, gathering and disseminating data required several meetings and many emails.

5.4.8 Result 8 – Experimental DDA confirms literature claims of rapid application

DDA had a similar preference proportion for *'rapid application'* in literature and the experiment (Figure 28). A benefit of the DDA theme is rapid application for specifying automation systems according to Savoretti et al. (2017), and Sambasivarao and Deshmukh (1997) claimed DDA could speed up decision making by imposing structure on the unstructured problem of advanced manufacturing technology (AMT) implementation and making the information required to make choices easily available. The experimental DDA did not progress to a stage where the speed of application could be assessed as the machines analysed were all bespoke providing too few similar parts that could be neatly categorised and the data from past cases was often incomplete. However, it became clear that the design and build of the DDA, similar to the QM&S above would be extremely time consuming. As noted in Section 5.3.1 a difference can be made between speed of constructing a tool and its application. Due to the unfinished experiment, this neither confirms nor contradicts the claims in literature that DDA can aid rapid application. The main finding was that a DDA is time consuming to construct but this could be more relevant to the *'for small business/resources'* criterion as the construction time could be designated as a resource issue and not affect the speed of use once completed.

5.4.9 Result 9 – Experimental flowchart contradicts literature on usability

Flowchart had the highest preference proportion for *'usable by managers with technical knowledge'* in literature but had a much lower preference proportion in the experiment (*Figure 29*). The flowchart theme can be highly usable by managers with technical knowledge due to their graphical and simplified layout. Flowcharts were found to be easy to learn with little support or training by Fast-Berglund and Stahre (2013) and Erasmus et al. (2020), and Wehrmeister et al. (2014) claimed they reduce experience requirements. The use of flowcharts for organising tasks and information between those involved was claimed by Jung et al. (2017) to increase ease of use. The use of common language and simple syntax was suggested by Gingele (2001) to aid usability. Only De Felice, Petrillo and Zomparelli (2018b) claimed experienced and knowledgeable users were needed and proposed minimisation of human interaction to reduce error possibility. The experiment conducted by the author produced a flowchart of material and information flow, which was used to aid in planning automation of metal part production. It required little explanation to be used by managers and engineers internally and was shared with external providers who were able to understand it with only some minor queries. This supports the assertion in literature that one of the main advantages of flowchart methods is their ease of use for managers with minimal technical knowledge through being generally self explanatory and graphical. However, the team that helped to construct the flowchart and those that used it were experienced in the automation field and a less knowledgeable team may have struggled, supporting the argument of De Felice, Petrillo and Zomparelli (2018b). To test this in more detail in future research a flowchart could be attempted by participants with low experience and knowledge of automation with opinions gathered and analysed. Another major issue influencing usability was the lack of guidance on how to implement the proposals produced, for example, which process to begin modifying first. This requires further investigation and perhaps combination with another method such as AHP to assist decision-making.

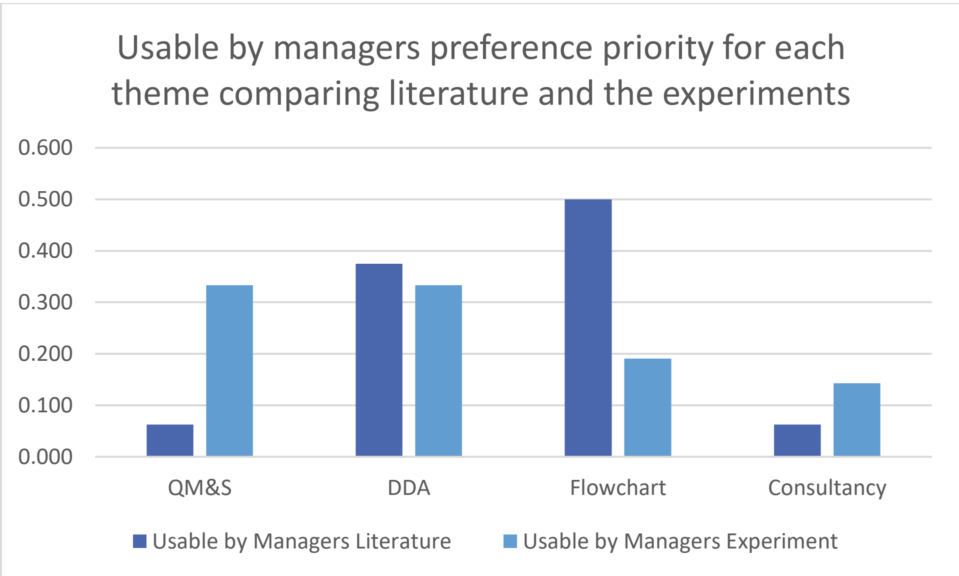


Figure 29: Preference priority of each theme for the criterion 'usable by managers with technical knowledge', comparing literature and the experiments.

5.4.10 Result 10 – Experimental QM&S contradicts literature on usability

QM&S had a very low preference proportion for *'usable by managers with technical knowledge'* in literature but had the joint highest preference proportion in the experiment (*Figure 29*). Specifying automated manufacturing systems requires specialised knowledge by users but in the reviewed QM&S literature, only Guschinskaya et al. (2011) and Bertolini, Esposito and Romagnoli (2020), noted ease of use as an important factor for implementation. It could be inferred that the other authors accept that knowledge and experience would be needed to use their approaches and this was explicitly stated by Ng, Urenda and Svensson (2007). As the author was investigating within a company providing automation solutions, the managers possessed a deep understanding of linking requirements and solutions. However, due to the rapid advancement of technology and the proliferation of possible options even the 'experts' do not know every possibility for automation or are able to compare them to decide which to use and they would benefit from a QM&S approach. Additionally, users of the technology, while possessing specialist knowledge on its capabilities may not be experts in other aspects of the complete system.

Ease of use can be greatly improved with a simple graphical user interface (GUI) for inputting data and displaying results according to Rahman and Mo (2012b). The interface developed during experimentation used Microsoft Excel, which aids ease of use, as most managers are familiar with it. A simple GUI could make an approach useable, as the manager does not need to know how results are calculated, however this "black box" approach can lead to mistrust. Other issues identified in literature were the acquisition of data being difficult (Wuest et al. (2016) and Lechevalier et al. (2018)), and QM&S requiring a lot of work to set up according to Fischer, Obst and Lee (2017). These were confirmed in the experiment by the lack of accurate data and the large amount of time required configuring the tool. However, if the tool was created already and the required data was available then inputting that data and running the simulation would be relatively easy.

5.4.11 Result 11 – Experiment confirms literature claims on usability of DDA

DDA had a high preference proportion for *'usable by managers with technical knowledge'* in both literature and the experiment (Figure 29). The DDAs of other researchers were designed to be usable by managers with technical knowledge by reducing the knowledge and experience needed to specify AMT through enabling managers to navigate the choices required. Hamzeh et al. (2018) developed a technology selection framework, Ramis et al. (2015) used a knowledge driven and ontology based approach, and Sambasivarao and Deshmukh (1997) offered options and tools to compare the relative benefits of automation choices. Savoretti et al. (2017) also noted that these decisions require specialist knowledge unless an approach is used to simplify or support them. In the reviewed papers only Shehabuddeen, Probert and Phaal (2006) claimed that knowledge and experience would still affect the success of a project when using DDA. The DDA produced in the experiment was extremely simple and as such could be used by anyone with some experience of office software. Although limited, the experiment does support the claims in literature that DDA can be useable by managers through a simple interface supporting decisions by providing information.

5.4.12 Result 12 – Experiment confirms literature claims on usability of consultancy

Consultancy had a low preference proportion for *'usable by managers with technical knowledge'* in both the literature and experiment (Figure 29). Reviewed papers in this theme were critical of its utility for this criterion with authors as far back as Thompson (1995) claiming existing methods were not easy to use. Authors attempted to overcome this in their consultancy approaches by targeting them towards managers and engineers, considering risks and publishing guidance for use. One example is Baines (2014) who set out the what, why, how, who, outcome and risks of each step of their method in a handbook for practitioners. Another is Farooq and Obrien (2012 and 2015) who tried to help managers with technology selection using a decision-making framework and including risks and threats. Testing on naïve participants was used by Fast-Berglund and Stahre (2013) to validate that their method was easy to use. The author also used untrained subjects (further described in Section 3.4.4 Testing) to test the developed tools by asking them to get a result with only basic instruction on the purpose of the experiment. This was a useful process for eliciting ideas for additions, opinions on features and areas requiring improvement. These ranged from graphical or presentation changes and wording suggestions through extra sections to complete redesigns. Participants also requested more explanation about how to use the tool and its purpose. Usability can be forged through free exchange of opinions with practitioners and repeated testing. However, there can be a trade-off between usability and detailed results similar to the inverse relationship between speed of application and level of detail. The simple tools developed during the experiment were easy to use after some explanation but did not cover the whole specification process, so knowledge and experience would still be needed to fill in the many gaps supporting the claims in literature that approaches in this theme are not easy to use.

5.4.13 Result 13 – DDA and Consultancy highest preference for considering non-financial factors

DDA and Consultancy themes had the highest preference proportion for 'considers not just the financial costs and benefits' in both literature and the experiments (Figure 30). This criterion was discussed as being important by Asawachatroj et al. (2012), Hamzeh et al. (2018), Sambasivarao and Deshmukh (1995 and 1997), and Goh et al. (2020), within the DDA theme. Hamzeh et al. (2018) incorporated the opportunities and threats of adopting new technologies by including risk calculations, quality and lead-time to complement that of product cost and provide a fuller picture. Factors other than financial ones were examined in detail by Sambasivarao and Deshmukh (1995), who presented tables of research that considered human, social, strategic and technological issues. Their DSS approach published a couple of years later (Sambasivarao and Deshmukh, 1997) included; attributes of alternatives, details of the initial investment, project life, cash flow, interest rates, priorities and risks. Most recently, Goh et al. (2020) considered variability of components in their decision support tool. The experimental DDA had very limited scope but did include properties and specifications of options to inform choices. This indicated that their inclusion was possible, but unfortunately no testing could be done because the tool was not completed, leading to weak evidence to support the claims in literature.

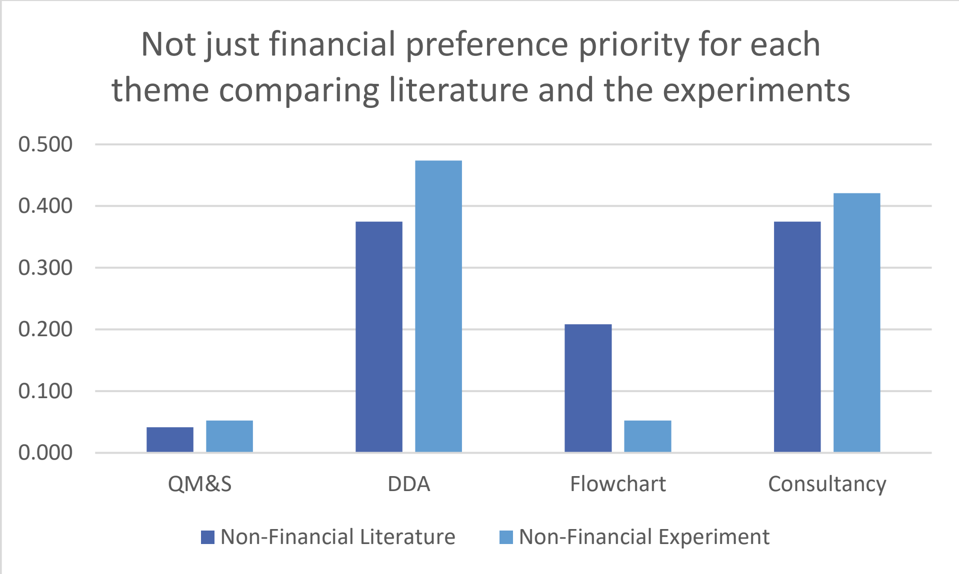


Figure 30: Preference priority of each theme for the criterion 'not just the financial costs and benefits'', comparing literature and the experiments.

The Consultancy theme is well suited to consider not just the financial costs and benefits, as it can elicit and gauge opinions on intangible factors according to Larsen (1994) who used a series of workshops to guide companies into considering company wide costs and benefits of AMT investment. A common complaint is the difficulty of assessing and comparing intangible benefits according to Chan, et al. (2001) who reviewed papers on justification of AMT and found evidence that the benefits of AMT are difficult to quantify, but this can be overcome using strategic criteria such as perceived market leadership. Another option proposed by Ordoobadi and Mulvaney (2001) was to first calculate the gap between expected economic return and desired economic return then consider system wide benefits analysis to bridge the gap. Some non-financial benefits can nevertheless be given values and Hamzeh et al. (2018) recommended considering the superior quality and shorter lead times made possible by automation. The experimental consultancy tools developed by the author addressed the criterion through the safety calculations and robot selection tools that could be used to consider factors other than financial when making automation choices. Other tools such as the ROI calculator were purely monetary but overall the experiment supports the claims in literature that the Consultancy theme is well suited to address this criterion.

5.4.14 Result 14 – QM&S lowest preference for considering non-financial factors

QM&S had the lowest preference proportion for *'considers not just the financial costs and benefits'* in both the literature and the experiments (Figure 30). Consideration of costs and benefits outside the financial is intrinsically problematic with QM&S. Intangibles such as image of the company and environmental impacts cannot be chopped up into discrete pieces to be inserted into a computer program. This issue has been discussed by many authors criticising QM&S methods including Hamzeh et al. (2018), Alfnes et al. (2016) Lindstrom and Winroth (2010), Thomassen et al. (2016), Sambasivarao and Deshmukh (1997), Ordoobadi and Mulvaney (2001), Farooq and O'brien (2012 and 2015), and Roy et al. (2017). Non-financial costs and benefits have also been noted as a limitation by some the exponents of QM&S approaches (Chen and Small (1996) and Chan, Kwong and Tsim (2001)). The author did not find a way to include these intangibles in the experimental approach, which backed up the findings from literature and this is one of the key weaknesses of this approach to automated manufacturing system specification. One possible solution would be to combine with approaches from a different theme for example consultancy.

5.4.15 Result 15 – Experiment flowchart contradicts literature claims for non-financial factors

Flowchart had a lower preference proportion for *'considers not just the financial costs and benefits'* in the experiment than in literature (Figure 30). Due to the non-quantitative nature of most flowchart methods, they can consider costs and benefits other than financial ones. Perhaps for this reason only De Felice, Petrillo and Zomparelli (2018b) explicitly mentioned this as a criterion for their method. However, Seth et al. (2017) highlight the lack of quantities in most flowchart approaches, making them unsuitable for addressing even the financial costs and benefits. The non-financial benefits were considered and discussed when constructing the experimental flowchart including the reputational benefits of deploying advanced technology in the processes of a company that implements automation. Non-financial costs could include the possible morale change of staff who must change their job role or tasks due to the new systems. However, these were not included in the experimental flowchart as it dealt with the physical movement of material and data through the business. Another flowchart specifically for consideration of these intangibles could be produced as part of the process, perhaps as a first step to inform choices in the modelling of tangible factors. As the costs and benefits, whether tangible or intangible were not included in the flowchart this led to a low preference and contradicted De Felice, Petrillo and Zomparelli (2018b) although the limited scope of the experiment does not provide strong evidence for this.

5.4.16 Result 16 – Experimental QM&S contradicts literature claim of low resource use

QM&S had a high preference proportion for the criterion 'for small business/resource use' in literature but was much lower in the experiment (Figure 31). SMEs require a simplified and cost effective alternative to commercially available modelling software according to Cavalieri et al. (2004), Saberi and Yusuff (2012), Oppelt, Wolf and Urbas (2015) and Constantinescu, Francalanza and Matarazzo (2015). The QM&S approach used in the experiment was based on free or cost effective software, minimising resource costs and agreeing with these researchers. QM&S approaches were criticised by Chen, Feng and Zhang (2003) for the large amount of data required and data availability for input to the authors' experimental simulation was an issue as exact processing times for each station were required. Fischer, Obst and Lee (2017) find fault with the large amount of work needed to set up, and the experiment supports this as developing and configuring the user interface and simulation program took hundreds of hours contributing to the low preference proportion of QM&S for this criterion and contradicting the claims of several researchers.

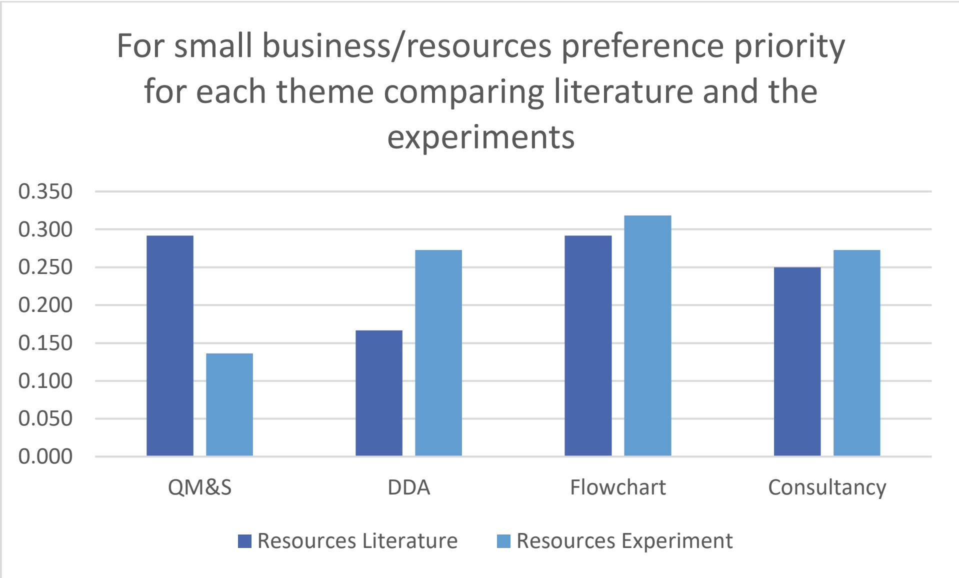


Figure 31: Preference priority of each theme for the criterion 'for small business/resources', comparing literature and the experiments.

5.4.17 Result 17 – Experimental DDA contradicts literature claim of high resource use

DDA had the lowest preference proportion for the criteria *'for small business/resource use'* in literature but was higher in the experiment (Figure 31). The deployment of DDAs in SMEs was not widely discussed in literature. Hamzeh et al. (2018) stated in their conclusion that many developed specification methods cannot be scaled down to small businesses but did not provide any evidence that their approach could be. The DDA developed by the author was specifically for an SME. An advantage of implementing in a small business is the low number of past cases to consider which speeds up database creation, but this can also reduce generalisability of the data. One disadvantage discovered in this case was the poor quality of records kept. It is hoped that in a larger company, stringent recording practices would provide data that are more reliable. The issue of poor data recording can be particularly prevalent in SMEs as they often do not have ERP/MRP systems or well thought out procedures for data recording, simply recording data in response to specific problems encountered in the past that caused loss of revenue or customers. Another issue, which applies generally to the DDA approaches for automation specification is the huge number of options available. This can lead to a high resource cost to complete the database, although once completed it could be distributed to many automation companies, spreading the cost.

5.4.18 Result 18 – Flowchart and consultancy both confirmed as good for small business

Flowchart and Consultancy had a high preference proportion for the criterion *'for small business/resource use'* both in literature and the experiment (Figure 31). Flowchart methods can be useful for small businesses due to the low resource requirements. Small businesses were specifically addressed by Qurashi (2000) using a company wide approach to aid implementation and Mahmood et al. (2017) discussed using CONSENS (CONceptual design Specification technique for the Engineering of complex Systems) for FMS implementation in SMEs. The research environment of the experimental flowchart was a small business so it was targeted towards this. Simple and cost effective software was used reducing resource cost but the process required group participation, which increased the use of resources. As discussed earlier the full validation of implementing the designed solution was not achieved but the limited results support the literature.

For the consultancy theme, the difficulties of AMT adoption for small businesses are mainly due to a lack of knowledge and financial resources according to Ordoobadi and Mulvaney (2001), and existing methods cannot be readily scaled down for SMEs in the opinion of Hamzeh et al. (2018). The experimental tools in this research were developed and tested within an SME with specific needs such as lack of knowledge and resources as the main considerations. This led to a selection of tools that were targeted to an SME for a specific task by providing the knowledge and reducing the resources required. The approach could be generalisable to other SMEs performing similar activities, as they will have similar needs and limitations. Consultancy was criticised by Teufl and Hackenberg (2015) and Qin, Liu and Grosvenor (2016) for a high resource cost. This was not found to be a large issue in the experiment as widely available spreadsheet software was used and could be completed by a single engineer but development of the tools required highly skilled workers.

5.4.19 Result 19 – Flowchart and consultancy confirmed as good for ETO products

Flowchart and consultancy had the highest preference proportion across both literature and the experiment in the criterion *'for ETO products'* (Figure 32). Applying flowchart methods for engineer to order products was attempted by Thomassen, Alfnes and Gran (2015) through proposing changes and additional steps and Seth et al. (2017) suggested using methods to simplify and approximate data to be able to apply VSM to ETO products. The automation system mapped with the experimental flowchart (Figure 5) can be considered an ETO product and the method was able to simplify at the top level but also provide further levels of detail through decomposition down to component level. This showed that flowcharts could be used as part of the planning stage for ETO products due to their ability to simplify and approximate supporting the claims of Seth et al. (2017).

Few reviewed papers in the consultancy theme refer to the challenges of specifying engineer to order (ETO) products. Boothroyd (2005) uses the narrow definition that automated production machines are one of a kind and so no example exists to compare with for planning, which requires managers to use knowledge and experience in design. A broader definition would include things like sewing machines, which are produced in great quantity but this research would be more relevant to the machine that produces the sewing machines. An attempt to overcome the problems of ETO products was made by Thomassen, Alfnes and Gran (2014), included again here as their research spans flowchart and consultancy, who further developed VSM to provide support for ETO products and Adrodegari et al. (2015) who targeted ETO manufacturing but mainly considered production planning and control. The consultancy tools in this research were focussed on ETO products consisting of bespoke automated production machines. This required consideration of the huge variety of factors and options in a format limited by consultancy time and ease of use. The conclusion was that a tool could be useful to gather generic information common to all projects such as the desired cycle time or available footprint but consideration of the process would still require the knowledge and experience of the engineers involved, which for this criterion practitioners can be assumed to possess.

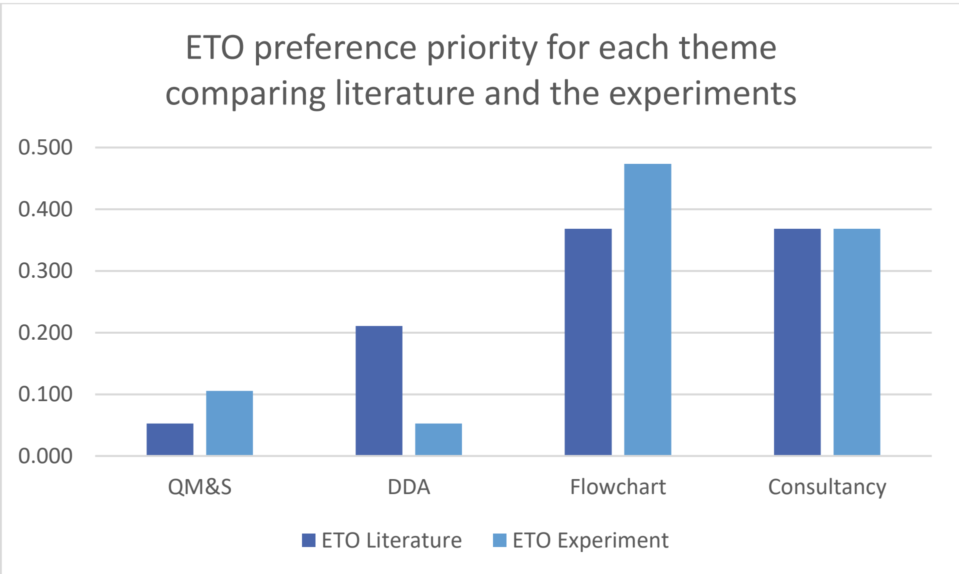


Figure 32: Preference priority of each theme for the criterion 'for ETO products', comparing literature and the experiments.

5.4.20 Result 20 – QM&S and DDA confirmed as least effective for ETO products

QM&S and DDA had the lowest preference proportion in both literature and experiment for the criteria *'for ETO products'* (Figure 32). None of the reviewed QM&S papers was targeted specifically towards engineer to order (ETO) products. One reason could be the relative lack of research into ETO production compared with that of high volume, low variety products. The methods in this theme are mainly applicable to repeating processes due to the large amount of data and set-up time required. It may not be cost effective to create a new model or simulation for a product that will only be produced once, although commercial software is available to model automated production systems it is mainly for designing the factory layout and identifying bottlenecks. However, bespoke automated machines are high value, but also high risk, and investment in modelling at the planning phase could result in large savings through preventing costly mistakes. The experiment showed modelling of these systems was possible but accurate data is required. When data is not available, for example cycle time of a process that has not been designed yet, it can be estimated but this will introduce inaccuracy. This is compounded by the issue that to be general enough to cover all possible applications, the level of abstraction must be raised. In this experiment, the granularity was at the level of machine actions such as feed, assemble, or transform, but this does not help with selection of components. This confirmed the unsuitability of QM&S for ETO inferred from the lack of reference to it in literature.

The only research paper in the DDA theme that specifically mentioned ETO products was Savoretti et al. (2017) who criticised DDA because ETO specification required selecting from too many alternatives. The experiment concurred finding DDA to be the worst performing theme for this criterion, mainly due to the huge range of options, some of which will only ever be used once making entry to a database unhelpful. This could be ameliorated using a formalised ontology such as those of Baldwin, Rose-Anderssen and Ridgeway (2014) or Agyapong-Kodua et al. (2013, 2014) to impose order on a database of components. Another problem was the large number of suppliers offering similar products and each with a range of characteristics, for example sensing distance of a sensor or pitch and lead of a ball screw, making the data collection required extremely time consuming. Furthermore, the rapid evolution of technology in automation could render the database obsolete or require constant updating to stay relevant. A possible solution to this could be to link to external databases of components and selection guides provided by the suppliers. However, these can be extremely complex; for example, Siemens have five different online tools just for selection of drives making comparison of offerings from one company difficult without even considering other suppliers.

5.4.21 Result 21 – Experiment contradicted literature on QM&S at the early stage

QM&S had the highest preference proportion in literature but the lowest preference proportion in the experiment for the criteria *'usable at the early stage of planning'* (Figure 33). QM&S generates the greatest benefit when used at the early stage of planning as it can predict problems and highlight the most effective solutions according to Bornschlegl et al. (2015), Ferrer et al. (2015), Heilala et al. (2006), and Salmi et al. (2015), (2016) and (2018). However, the reliance of the approach on data is a problem as accurate data is sparse at the early stage of planning a production system making calculation of accurate results difficult. This swayed the author towards more coarse-grained models to begin with that can be refined as more data becomes available. The experiment showed that the results were only as good as the input data, which had to rely on estimates, but also suffered from the risk of mistakes and distortion due to problems with the model or simulation supporting Chen, Feng and Zhang (2003), Lechevalier et al. (2018) who criticised use of QM&S at the early stage. Nevertheless, the views of the supporters of QM&S for this criterion were also supported through comments from automation engineers and managers and the authors own experiences when specifying automated machines. These were that modelling at the early stage could save large amounts of time and money. However, this is with the caveat that the modelling must be fast and accurate, two competing principles. Finally, the reliance of methods in this theme on detailed information reduces the ability to use them at the early stage of planning due to the lack of accurate data and conversely the huge numbers of available options. Overall, the experiment refutes the prevailing opinion of other researchers that QM&S is suitable at the early stage of planning.

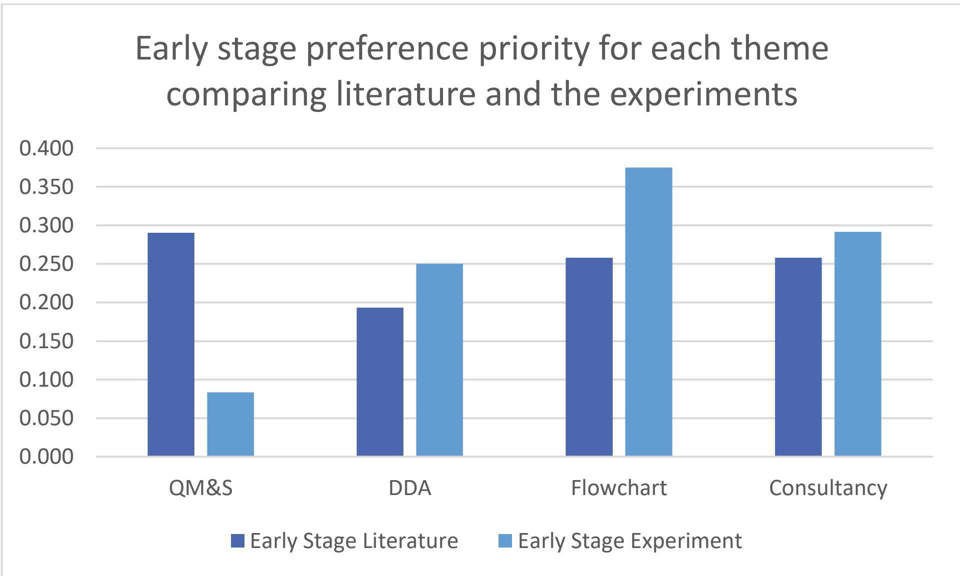


Figure 33: Preference priority of each theme for the criterion 'usable at the early stage of planning', comparing literature and the experiments.

5.4.22 Result 22 – Experimental flowchart most usable at the early stage of planning

Flowchart had the highest preference proportion in the experiment for the criteria *'usable at the early stage of planning'* (Figure 33). Being useable at the early stage of planning was noted as an important factor by Fast-Berglund and Stahre (2013), Mazak and Huemer (2015) and Roy et al. (2011). They claim that flowchart methods are readily useable at the early stage of planning, as they do not need detailed and accurate information to construct. The authors' flowchart was constructed at a very early stage of the development using a specification developed internally and information from multiple sources including research papers and technology vendors to create options. The uncertainty of direction and lack of data on options did not affect the construction greatly, and the flowchart was found to be a useful tool for exploring and sharing ideas, which supports the claims found in literature that flowcharts are able to incorporate incomplete or low detail information and still produce results that could guide subsequent planning stages. In a complete approach to automation specification flowcharts could represent a first step when planning followed by further investigation using tools that are more detailed from another theme.

5.4.23 Result 23 – Experiment confirmed literature on DDA and Consultancy at early stage

DDA and Consultancy themes had a similar preference proportion in literature and experiment for the criteria *'usable at the early stage of* planning' (Figure 33). The issues faced when trying to make decisions at the early stage of a project were considered by Savoretti et al. (2017) in their DDA, particularly the implications a choice at this stage has for creating cost estimations that are not accurate. The database created by the author could be used at the early stage of planning to assist in selection of processes and components to achieve the required task. However, due to time limitations, a complete database was not possible and the tool was not used in planning of any projects. Opinions on the database were sought from engineers and managers. The general view was that while a database could be a useful resource for early planning the internet already provides this service. Unfortunately, the proliferation of databases available through an internet browser makes comparing options time consuming. This could be partially solved using a structured approach or procedure to guide the user and ensure consistent consideration of alternative options. The limited nature of the experiment meant that it could not fully support or contradict the literature.

The ability of their approach to be useable at the early stage of planning was claimed by Fast-Berglund and Stahre (2013), whose research spans both flowchart and consultancy themes, through involving all parties from the start and drawing in information. Teufl and Hackenberg (2015) championed analysis of requirements early in the automation process to reduce risk of project failure using a model based classification approach, and system design using early product information was proposed by Sinnwell, Krenkel, and Aurich (2019). The tools tested experimentally were targeted towards the early part of the specification process before the customer order has been won. This is a critical stage for the success of a business as it leads to securing profitable work. Engineers and managers involved are tightly constrained by time as without the guarantee of an order any effort expended may be wasted. Additionally, they must make decisions with limited information to outline how a machine will function, its main elements, and provide a price estimate that provides a healthy profit for the company while being within the means of the customer and favourable against competitors bids. The designed tools used similar ideas to those found in literature to analyse requirements and use any available data such as early product information. Tools were targeted to specific needs within the specification process such as calculating the return on investment (Figure 7) to define a price ceiling over which the proposal would not be successful. Consultancy may be an excellent tool not only for exhaustively designing the machine to the specification but also to engage the customer in the process making them feel integral to decisions rather than a passive receiver and approver of ideas. This supports the research of Fast-Berglund and Stahre (2013) about involving all participants from the start.

5.4.24 Result 24 – Consultancy most successful in practical terms

The most successful experiment in practical terms was in the consultancy theme as some of the developed tools were used on actual projects to improve accuracy of cycle time and safety estimates. However, the results of the AHP analysis suggest that DDA would be the most appropriate theme for specification of automation when all criteria are considered (Figure 27). Some of the reasons for this were practical such as the difference in scale between the small tools developed for consultancy and the large database of past cases that would be required for DDA. In industry, the widespread use of enterprise resource planning (ERP) software could indicate that the DDA theme has already been accepted as a good solution. In the limited experience of the author with ERP implementation in the host company, much time and money were invested with no benefit in return so far. However, once an ERP system is fully implemented large efficiency gains in planning and resource allocation would be expected due to availability of accurate information and tracking of orders through the system.

5.4.25 Result 25 – Experiment disagreed with literature on QM&S for usable and early stage

The experimental results disagreed with the literature on the applicability of the QM&S theme for the *'usable by managers with technical knowledge'* and *'usable at the early stage of planning'* criteria as shown in Figure 34, where the numbers are the relative preference proportions against the other three themes. Papers by Michalos, Makris and Mourtzis (2012), Bornschlegl et al. (2015), Ferrer et al. (2015), Heilala et al. (2006), Salmi et al. (2015), (2016) and (2018) claimed QM&S useful at the early stage of planning but the experiment found QM&S less usable at the early stage due mainly to the poor quality and scarcity of available data. Conversely, Fischer, Obst and Lee (2017), Kim and Lee (2013), Lechevalier et al. (2018), Long, Zeiler and Bertsche (2016), Ng, Urenda and Svensson (2007) and Wuest et al. (2016) criticised QM&S as being difficult leading to a low preference proportion for the *'usable by managers with technical knowledge'* criterion, but the experiment assigned QM&S a higher preference proportion due to the GUI and computerised calculations aiding ease of use.

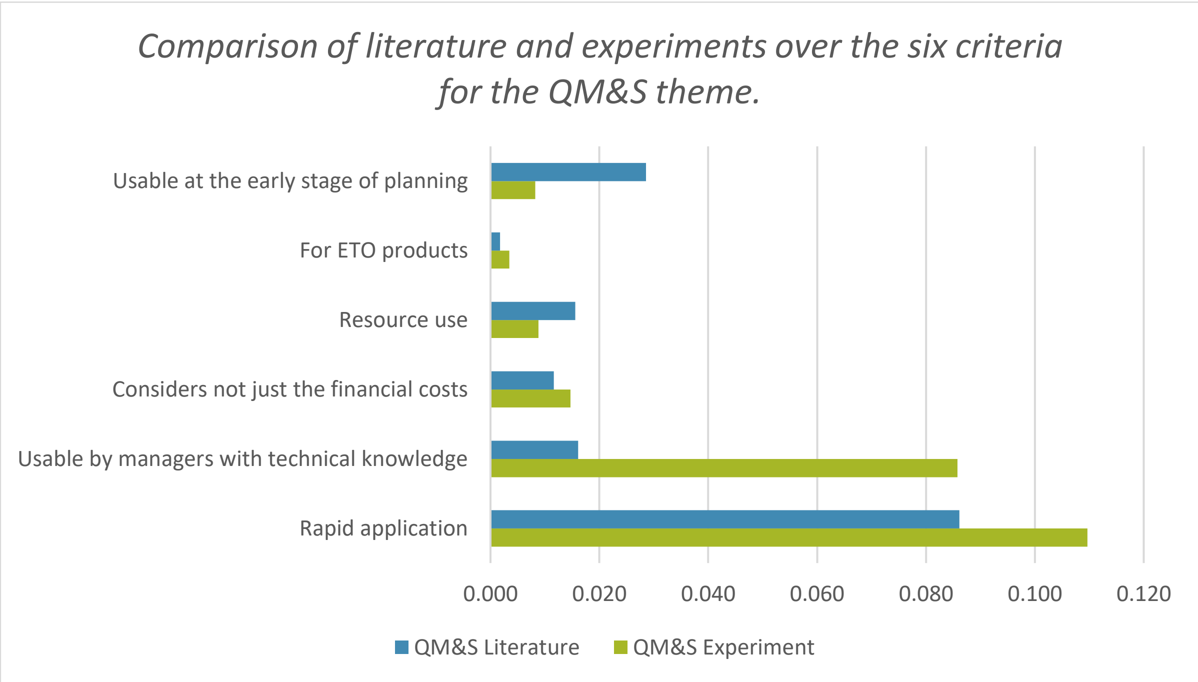


Figure 34: Comparison of literature and experiments over the six criteria for the QM&S theme.

5.4.26 Result 26 – Experiments confirmed literature claims for DDA

The preference proportions for each criteria in the experiments generally confirmed the claims of other researchers for the DDA theme (Figure 35). However, confirming the findings of other researchers cannot be claimed as an interesting result from which to discuss or draw conclusions.

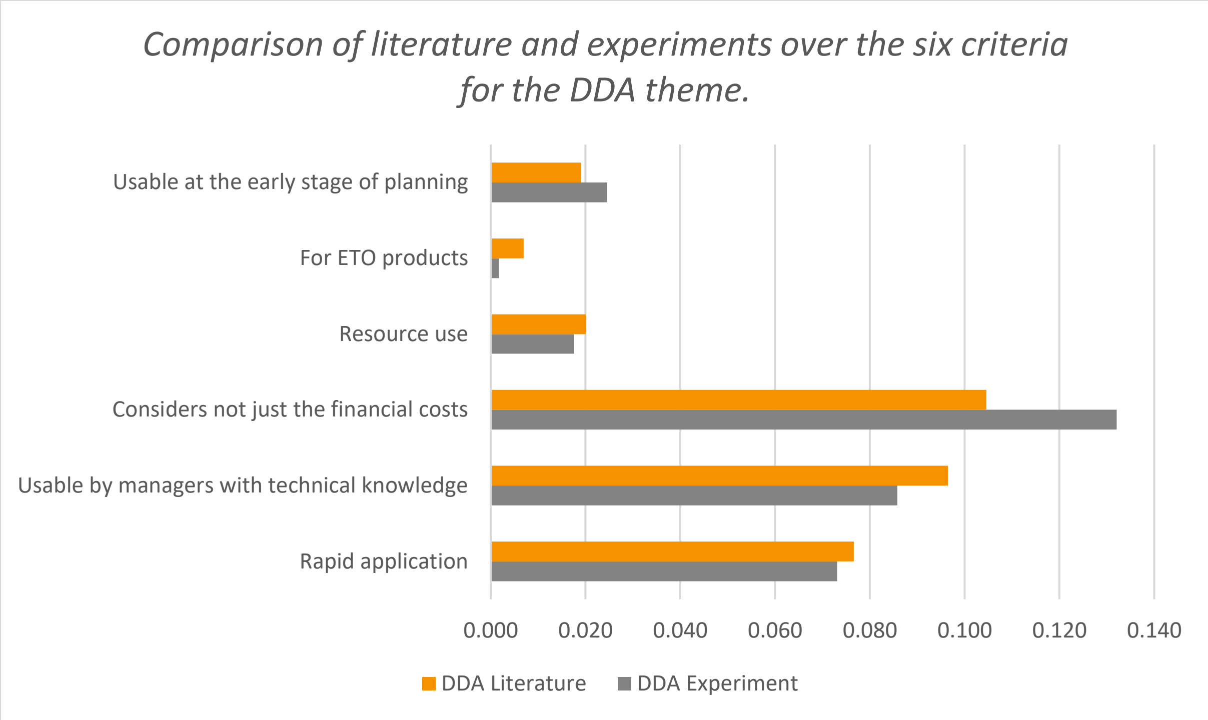


Figure 35: Comparison of literature and experiments over the six criteria for the DDA theme.

5.4.27 Result 27 – Experiment disagrees with literature on flowcharts for early stage and ETO

Figure 36 shows that the preference proportions of the Flowchart theme were higher in the experiments than the literature for the *'usable at the early stage of planning'*, *'for ETO products'* and *'for small business/resources'* criteria. The preference proportions were also lower for the '*rapid application'*, *'usable by managers with technical knowledge'* and *'considers not just the financial costs and benefits'* than those from literature, disagreeing with the claims of other researchers. The lower preference in the three higher priority criteria led to the large difference in overall preference for the Flowchart theme in Result 3.

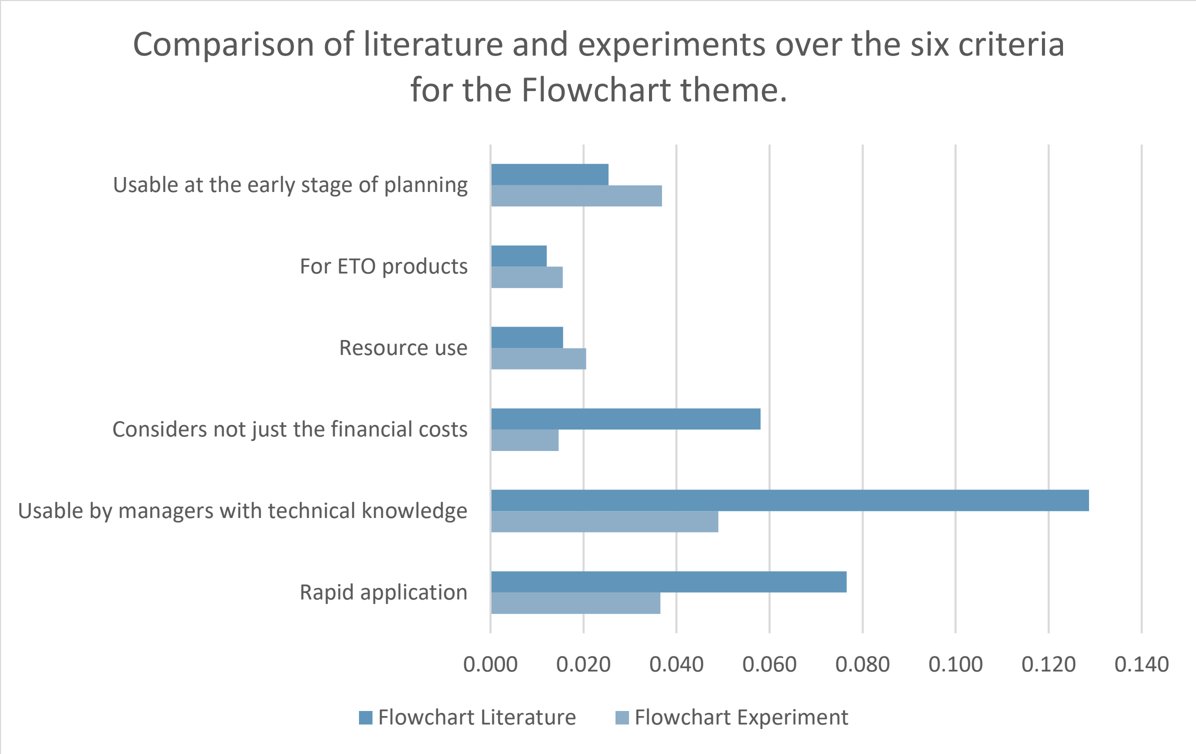


Figure 36: Comparison of literature and experiments over the six criteria for the Flowchart theme.

5.4.28 Result 28 – Experiments confirm literature claims on consultancy

The preference proportions from the experiments and literature overlap well for the consultancy theme, supporting the claims of other researchers (Figure 37). As mentioned previously, confirming the findings of other researchers does not yield interesting results or conclusions but for completeness, it is important for them to be noted.

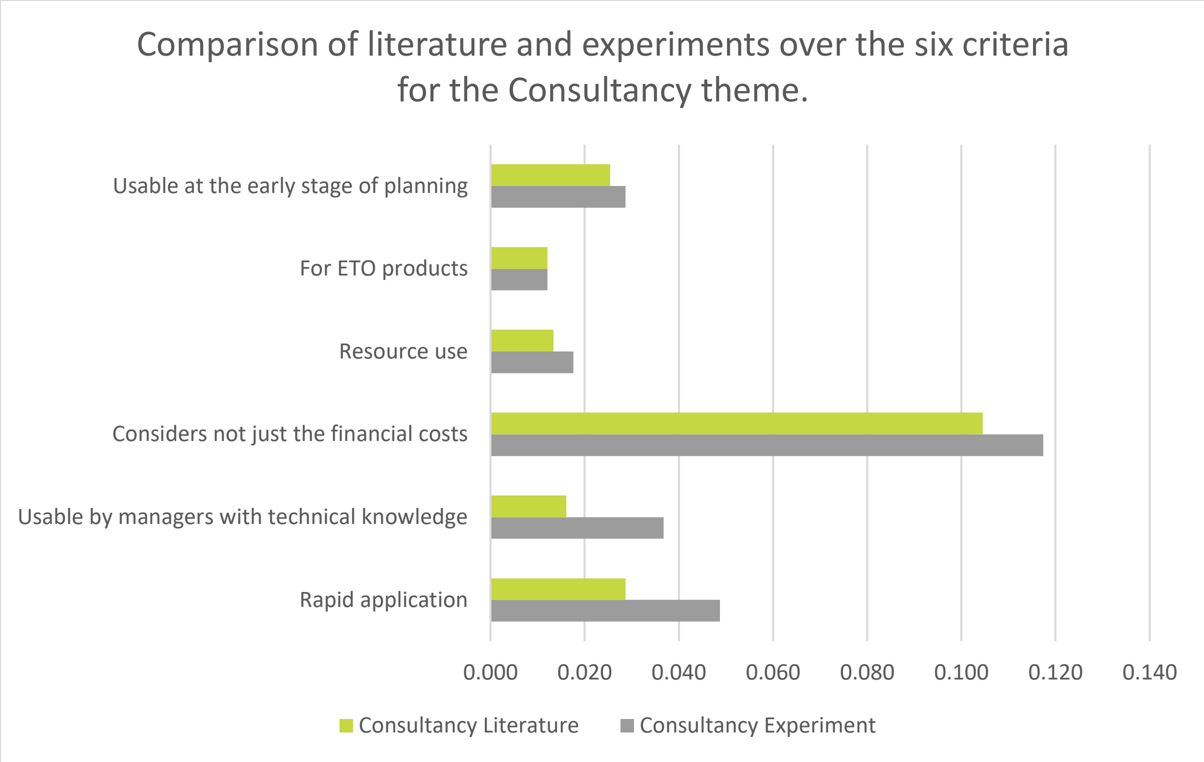


Figure 37: Comparison of literature and experiments over the six criteria for the Consultancy theme.

5.5 Summary

This Chapter has discussed the relative strengths and weaknesses of the four themes across the six criteria and compared current literature with the results of the experiments conducted within the host company. Overall, the DDA theme was most successful for automation specification in literature and this was corroborated by the experiments. QM&S had the lowest preference in literature but this was contradicted by the experiment, in which the lowest preference was for the Flowchart theme. Some results supported the existing research (Table 39), while others contradicted it (Table 40). To aid future researchers in development of approaches to specify automation the most and least applicable themes for each criteria in literature and the experiments were presented in Table 41 and Table 42 respectively with reference to the results discussed above.

Table 39: Literature claims confirmed by the experiments.

Literature claims confirmed by the experiments		
Theme	Strengths	Weaknesses
QM&S	*Rapid application* – Result 5	*Consider not just financial costs and benefits* – Result 14
DDA	*Consider not just financial costs and benefits* – Result 13	*For ETO products* – Result 20
Flowchart	*For small business/resource use* – Result 18 and *For ETO products* – Result 19	-
Consultancy	*Consider not just financial costs and benefits* – Result 13, *For small business/resource use* – Result 18 and *For ETO products* – Result 19	*Rapid application* –Result 6 and *Useable by managers with technical knowledge* – Result 12

As noted above, Table 39 presents the literature claims that were confirmed by the experiments along with the result number that discusses these in detail. These results confirm accepted views. However, some value can still be claimed from aggregating the views of other researchers and testing them to lend weight to their observations.

The QM&S theme's main strength was the '*Rapid application*' criterion due to computerisation and its main weakness the '*Consider not just financial costs and benefits*' criterion as these are generally not quantifiable. DDA excelled in considering not just the financial costs and benefits using past experience and guiding choices but struggled with ETO products due to the enormous variability in components and options. The flowchart theme was best for ETO products due to their ability to simplify and approximate. The Consultancy theme scored highly in the criterion '*Consider not just financial costs and benefits*' through facilitating discussions on intangibles between stakeholders. Consultancy was also found to be highly applicable to ETO products by using tools to gather required information in a structured way. The main difficulties for consultation are the large amount of time and the high knowledge and experience required which caused low scores for *'Rapid application'* and '*Usable by managers with technical knowledge'*.

Table 40: Literature claims contradicted by the experiments.

	Literature claims contradicted by the experiments	
Theme	Strengths	Weaknesses
QM&S	*Usable at the early stage of planning* – Result 21, 22, *For small business/Resources – Result 16,*	*Useable by managers with technical knowledge* – Result 10, 12
DDA		*For small business/Resources –* Result *16, Usable at the early stage of planning* – Result 21, 23,
Flowchart	*Usable by managers with technical knowledge* – Result 9, 10, 11	-
Consultancy	-	-

The results noted in Table 40 are more interesting than those in Table 39 as they contradict other researchers so can be claimed to be new knowledge, although care must be taken that these results do not fall into the 'That's Absurd' category that Handfield and Melnyk, (1998) defined, through attacking strongly held assumptions. Another caveat is that due to the limited scale of the experiments these contradictions may only hold in the specific environment of the case study and not be generalisable across the industry. For example, the experimental QM&S was not successful as it struggled with the lack of accurate data available, but QM&S systems are used in many industries at the early stage precisely to solve the problem of unknowns.

Bearing in mind the above caveats, the experiments did contradict the literature for the QM&S theme in two criteria, finding it was not *'Usable at the early stage of planning'* due to the lack of reliable data, but was *'Usable by managers with technical knowledge'* because of the simple GUI and computerised calculations. For the DDA theme literature claims of low applicability to small businesses due to high resource use were contradicted by the experiment, although development of the DDA must be separated as once completed it could be distributed to many businesses so reducing the resource requirements. The claimed weakness of DDA for making decisions at the early stage was also refuted by the results of the experiment, which showed that the data and decision support provided were useful at the early stage.

Claims in literature that Flowchart methods were *'Usable by managers with technical knowledge'* were not supported by the experiment due to the high levels of technical knowledge required. This may be regarded as a particularly controversial finding, falling foul of the 'That's Absurd' caveat mentioned above as it is evident that flowcharts can be used and understood by those with little knowledge. However, the development of a flowchart may be straightforward but the information contained in this specific case is highly specialised and does require knowledge and experience.

Table 41: Most applicable theme for each criterion.

Criteria	Most applicable theme for each criterion Literature	Experiment
Rapid application	QM&S – Result 5	QM&S – Result 5
Useable by managers with technical knowledge	Flowchart – Result 9	QM&S/ DDA – Result 10, 11
Consider not just financial costs and benefits	DDA/Consultancy – Result 13	DDA/Consultancy – Result 13
For small business/Resources	QM&S – Result 16, Flowchart – Result 18	Flowchart – Result 18
For ETO products	Flowchart/Consultancy – Result 19	Flowchart/Consultancy – Result 19
Usable at the early stage of planning	QM&S – Result 21	Flowchart – Result 22

Table 42: Least applicable theme for each criterion.

Criteria	Least applicable theme for each criterion Literature	Experiment
Rapid application	Consultancy – Result 6	Flowchart – Result 7
Useable by managers with technical knowledge	QM&S/ Consultancy – Result 10, 12	Consultancy – Result 12
Consider not just financial costs and benefits	QM&S – Result 14	QM&S/ Flowchart – Result 14, 15
For small business/Resources	DDA – Result 17	QM&S – Result 16
For ETO products	QM&S – Result 20	DDA – Result 20
Usable at the early stage of planning	DDA – Result 23	QM&S – Result 21

'Rapid application' was sought by researchers in each theme but was best achieved by those in the QM&S theme as it was praised for being fast by many authors although this may not include gathering the required data. Once the approach is created, they can quickly convert data into useful information to guide implementation and this was supported by the results of the experiment. The least helpful theme for rapid application from literature was consultancy but in the experiment flowchart was found to be slowest. One of the key weaknesses of the Consultancy theme is the slowness due to the discussions required and iterative nature although this was not discussed by many of the papers reviewed. Two major caveats when considering these results are the limited time and resources available to progress the experiments, and the subjective nature of the AHP process to perform comparisons that could have introduced bias. The former of these may have had a large impact on the viability of the Flowchart theme in the experiment for this criterion.

Flowchart methods in literature were the most likely to be '*useable by managers with technical knowledge'* due to their familiarity and graphical basis, but the experiment contradicted the claims of usability, mainly due to the experience and knowledge required from participants in the process and lack of guidance on how to implement the proposals. Furthermore, low support in literature for the QM&S theme for this criterion was not corroborated by the experiment, which found it effective at simplifying the process due to the GUI simplifying the process and the software performing necessary calculations. However, when using AHP to compare options it must be noted that all preferences are relative due to the pairwise comparisons and these gains for consultancy and QM&S are partly due to the reduction of preference priority for the flowchart theme. Low usability by managers of the Consultancy theme was widely discussed in the literature, as the knowledge and experience of those involved influenced the chance of success. However, it is possible this was due to researchers focussing on weaknesses in order to identify a gap to justify their own research. The results of the experiment, although limited, support the literature as managers were assisted but only with small parts of the overall process. DDA approaches in literature targeted this criterion by leveraging the knowledge of those with greater understanding and being guided through a series of options with advice on how to choose at each step. The experiment found that DDA could support managers by providing information to help compare options.

The results of the experiment supported the claims by other researchers that Consultancy and DDA are most suited to consider costs and benefits other than financial ones. The main reason for these high preference proportions is the ability to include intangibles to inform choices and the possibility to discuss and vote on them; the Consultancy theme by facilitating the team to share and collate opinions, and DDA by providing data to compare options. Least effective for this criterion was QM&S, as approaches normally avoid assigning values to intangible factors because these are difficult to quantify and insert into a tool, closely followed by flowchart, and again the results from the experiment correlated well with those found in literature.

Quite an even spread of relative preferences with no large differences between the themes for the *'for small business/resources'* criterion was found through analysis of the literature and confirmed by the experiments. This could be due to 'for small business/resource use' being at the specific end of the criteria spectrum (Figure 1), resulting in those authors that focussed on this criterion in each theme claiming their work was able to overcome the challenges. Additionally, reducing resource requirements may be popular with researchers no matter which approach is taken as reducing resources is an easy target to hit in research and presents a gap in many fields of research. Companies are always trying to reduce resource use, so this could be an attractive way to sell the research to industry. The experiments contradicted the literature for the QM&S theme finding it less applicable to small businesses due to the large amount of resources required to develop a modelling system. Conversely, the experiments found DDA to be more applicable to small businesses than the literature as widely available tools such as spreadsheets could be used to collate and analyse data. The lack of resources was best addressed by the Flowchart and Consultancy themes as they were less complex and time consuming to develop. Unfortunately, these themes rely on the experience and knowledge of participants, which can also be regarded as a resource, showing some overlap between this criterion and *'usable by managers with technical knowledge'*. Another caveat is that due to the crude ranking system and closeness of the results inferred findings should be treated with caution.

Consultancy and flowchart were most suited to ETO products in literature and the experiments as they are more flexible to high variation due to their ability to work with low granularity, abstracted or estimated data and the claims in literature were supported by the experimental evidence. For ETO products, QM&S suffers from a reliance on accurate and complete data to input to the model or simulation, which often does not exist or is difficult to obtain, and DDA struggles with the proliferation of options. As automated production machines can be considered ETO products themselves, this suggests that consultancy and flowchart themes are most suited to designing them. However, once the early planning stage is complete, more accurate and precise data is available, and the number of options has been reduced, the other two themes could be used to test options and choose between them.

All themes included papers that attempted to address the early stage of planning an automation system but most successful was the QM&S theme as it models and simulates the problem to compare options. However, QM&S relies heavily on the availability and accuracy of the data and the experiment contradicts the literature finding QM&S much less effective for use at the early stage, due to the lack of good quality data available at this stage.

6 Conclusions

6.1 Introduction

The discussion in the previous Chapter developed arguments around the ideas discovered in the literature review and tested experimentally in the Results Chapter. This Conclusions Chapter summarises the evidence and relates the conclusions that can be derived from it to help answer the research questions:

How can an approach specify automation solutions?

Which criteria are important in an approach to specify automation solutions?

How well does existing literature meet the identified criteria?

The next section frames the research by describing the contribution to knowledge, followed by a section summarising the answers to the research questions and finally an overall conclusion section.

6.2 Contribution to knowledge

To be worthwhile for more than just improving the skills, knowledge and understanding of the author a research work must contribute something new to the existing body of scientific knowledge. This requires compliance with four criteria according to Handfield and Melnyk, 1998, 'not wrong', falsifiability, utility and parsimony. The author has used these criteria below to evaluate the contribution to knowledge of this research.

6.2.1 'Not wrong'

This concerns the approach and procedures of the researcher, whether the methodology is appropriate to the problem, is used correctly, and enough data is provided to evaluate correctness in the opinion of Handfield and Melnyk, 1998. They consider ‘not wrong’ to cover the difference between the question being ‘post hoc’ (after the fact) or ‘ad hoc’ (before the fact), the first of which is inappropriate to theory driven empirical research.

The multi-method qualitative methodology of this research, using literature review, semi-structured interviews and mini case studies fitted the aims of the research well, enabling exploratory work using open questions followed by evaluative studies to examine the quality of theories. This structure meant that the research questions formulated at the beginning required some modification during the course of the study. The original questions related to the creation of a new approach to specifying automation in manufacturing and the focus changed from creation of an approach to assessing current approaches and identifying the important criteria to construct an approach in the future. The re-worked questions reflected this and did not represent a change of direction but merely a contraction of scope.

6.2.2 Falsifiability

To be falsifiable the theory must be coherent enough to be refuted Bacharach (1989) tells us, and the major component of this is demonstrating causation for any relationships identified. Causation requires three conditions: cause and effect are related, cause occurs before effect temporally, and exclusivity through elimination of other explanations (Mill, 2011).

Demonstrating causation of the criteria for an approach involves examining their importance for the success of an approach in the specific environment of the study. Certainly, the first condition of cause and effect being related was fulfilled as the six criteria were backed by existing literature and confirmed to some extent through empirical data gathering and experimentation. Temporal relation of cause and effect is also relatively simple to justify for the six criteria. Rapid application results in an approach being faster to apply, usable by managers with technical knowledge makes an approach more accessible. Other criteria are more difficult to assess, such as considering not just the financial costs and benefits due to the wide range and intangibility of factors involved, such as reputational gain. Whether considering reputational gain in an approach would cause it to increase is unknown but could warrant further investigation using case studies or focus groups beyond the scope of this research. However, one finding is that considering reputational gain and other intangibles can allow approval of projects that do not meet financial justification criteria such as ROI.

As related by Handfield and Melnyk (1998), elimination of other explanations in operations management is difficult due to the high variability in the field research environment. This can be mitigated by considering the problem from different angles for example by questioning not only managers but workers on the factory floor as well. As the author was immersed in the research environment, assimilating these different viewpoints was possible in the context of this research as well as the application of approaches. This allowed testing of assumptions but not elimination of other explanations.

6.2.3 Utility

Utility or usefulness of research requires a theory dealing with an important problem, revealing new relationships or variables, exploring unexamined problems, and being interesting (Handfield and Melnyk, 1998). They expand 'interesting' by saying it cannot attack strongly held assumptions (That's Absurd), must be practically significant (Who Cares?), and not just confirm accepted views (That's Obvious).

Due to the large number of researchers working on the specification of automated manufacturing problem and the observable need in the practical research environment of the case studies the author concludes that this is an important problem. Relationships of the criteria to the problem were already known but the bringing together of the six important criteria for this problem, in this environment is thought to be novel. The overall problem of automation specification has been widely explored by many researchers but the examination of the specific case environment of this study is unique.

This research does not attack any strongly held assumptions so does not suffer from the 'That's Absurd' issue, but rather tests existing theory and in the main agrees, falling foul of the 'That's Obvious' requirement. However, an important caveat, described by Handfield and Melnyk (1998), is that in Operations Management practical knowledge has surpassed scientific knowledge and it is necessary to generate 'obvious' theories and test them. In the host business and others encountered during the research, the problem studied is practically significant and this could mean it is important in other companies as well.

6.2.4 Parsimony

A contribution to research should include only the necessary variables and content and extra complexity reduces the power of the work (Handfield and Melnyk, 1998). Originally, eight criteria were thought to be important and during the research, two were eliminated, as they were not supported well in literature, decreasing complexity without reducing the power of the remaining criteria. This can be said to have increased parsimony of the research. However, it may have been possible to remove more criteria, such as 'for small businesses/resource use' due to overlaps with other criteria and this could be another avenue for future work. The relationships between the criteria, either overlapping or contradicting each other were considered but could bear further investigation.

6.3 Conclusions drawn from research questions

6.3.1 Primary research question

The research focussed on specifying automation solutions at the early stage of planning when information is scarce and a multitude of options exist. The main research question addressed this by asking:

How can an approach specify automation solutions?

Many authors have attempted to answer this question or variations of it with varying levels of rigour and success. Four themes were identified in literature in terms of the methods used by researchers to aid in specification of automated machines. These were *QM&S, DDA, flowchart modelling* and *consultancy*. Each had strengths, weaknesses, and varying levels of utility for different stages or tasks within the specification of automation. These were analysed against the criteria in the secondary research question and compared using analytical hierarchy process (AHP). The DDA theme had the highest overall preference in literature and this was corroborated by the experiments (Section 5.4.1 Result 1). QM&S had the lowest preference in literature (Section 5.4.2 Result 2) but this was contradicted by the experiment, in which the lowest preference was for the Flowchart theme (Section 5.4.3 Result 3).

QM&S used numerical data, often computer based, to yield exact mathematical evaluations of solutions allowing comparison between options. This had the advantage of being concrete and evidence based allowing confidence in results and aiming towards optimal solutions. However, at the early stage the required data is often unavailable or inaccurate resulting in incorrect assumptions and inability to compute answers. The QM&S theme's main strength was the ‘*Rapid application’* criterion due to computerisation (Section 5.4.5 Result 5) and its main weakness the ‘*Consider not just financial costs and benefits’* criterion as these are generally not quantifiable (Section 5.4.14 Result 14).

Database decision aids use existing data, distilled using the knowledge of experts and a selection framework to guide the user in making decisions about specification of automation. They are excellent at guiding users with less knowledge and experience to make decisions by providing options and facilitating their selection through comparison of salient features. DDA excelled in the ‘*Consider not just financial costs and benefits’* criterion using past experience and guiding choices (Section 5.4.13 Result 13) but struggled with *‘for ETO products’* due to the enormous variability in components and options (Section 5.4.20 Result 20).

Flowchart modelling uses graphical information to evaluate current processes, assimilate ideas for improvements and share these between stakeholders. They are easy to understand and excellent for showing the connections between elements of a process and for explaining ideas for enhancement. However, except in some methods such as VSM that has quantitative elements, flowcharts do not consider quantities of material or time making comparison of options difficult. Conversely, this allows flowcharts to be used at the very early stage of planning when there is little data, to brainstorm ideas and quickly compare and assess them. The flowchart theme had the highest preference ‘*for ETO products’* due to the ability to simplify and approximate (Section 5.4.19 Result 19).

Consultancy was the term given to methods involving use of expert knowledge of both external and internal automation specialists and tools for cost and time calculations. Papers in this theme often proposed tools to assist decision makers with specific tasks during the specification of automation and this specialisation was mirrored in the experiments that produced practical tools for the host company. The theme is applicable at all stages of the automation specification process by utilising different tools for each. The Consultancy theme scored highly in the criterion '*Consider not just financial costs and benefits'* through facilitating discussions on intangibles between stakeholders (Section 5.4.13 Result 13). Consultancy was also found to be highly applicable to ETO products by using tools to gather required information in a structured way (Section 5.4.19 Result 19). The main difficulties for consultation are the large amount of time and the high knowledge and experience required which caused low scores for *'Rapid application'* (Section 5.4.6 Result 6) and '*Usable by managers with technical knowledge'* (Section 5.4.12 Result 12).

6.3.2 Secondary research question

Which criteria are important in an approach to specify automation solutions?

This was the secondary research question and criteria were identified through analysis of other authors' priorities during the literature review. Six important criteria were identified: *rapid application, usable by managers with technical knowledge, considering not just the financial costs and benefits, for small businesses/resource use, for engineer to order (ETO) products,* and *useable at the early stage of planning*.

Rapid application (Section 2.4.2 Rapid application) concerns the speed with which an approach can perform the necessary steps to produce a useful result. These include but are not limited to gathering information, processing it, comparing options and making decisions. Evidently faster approaches are preferred as the old cliché 'time is money' applies not only to the time spent on the specification task but also to the cost of opportunity lost for not implementing an improvement to efficiency sooner.

Usable by managers with technical knowledge (Section 2.4.3 Usable by managers with technical knowledge) is the ease of use and minimisation of knowledge and experience required. These make an approach more accessible to a wider range of people and businesses, increasing the chances that it will be used. This criteria also concerns minimisation of the possibility to make errors while applying an approach.

Considering not just the financial costs and benefits (Section 2.4.4 Consider not just the financial costs and benefits) assumes that the financial costs and benefits are already being considered. Other costs and benefits are intangible such as the morale of the workforce, or reputation of the company. While these are difficult to assign values to, they can nevertheless be important factors when making investment decisions, particularly when conventional cost benefit accounting does not provide a clear assessment.

For small businesses/resource use (Section 2.4.5 For small businesses/resource use), is particular to the environment of this research where resources are especially restricted, though reduction of resource use is generalisable to any business. The amount of resources required to develop and apply an approach to specification of automation should be minimised. This allows its application when there is pressure on resource use and consequently makes the approach more likely to be used.

For engineer to order products (Section 2.4.6 For engineer to order (ETO) products) is again specific to the environment of this research where the engineer to order products are the automated manufacturing systems produced for customers. This covers bespoke systems that are specified, designed and manufactured by an automation company as opposed to 'off the shelf' products. However, no papers reviewed took the perspective that the automated systems themselves were ETO products. The main difficulty with specifying ETO products is the large range of options and limited data on how they will perform in combination with each other.

Usable at the early stage of planning (Section 2.4.7 Usable at the early stage of planning) targets the very start of the specification process between deciding to automate something and beginning to choose components, further defined in Table 4. Questions that must be answered include 'what to automate?', 'why automate?', 'how to automate?' The problems to overcome are the lack of information and conversely the proliferation of different alternatives. Approaches that target the early stage must draw in information, while being robust to mistakes.

6.3.3 Supporting research question

How well does existing literature meet the identified criteria?

The claims in literature about the efficacy of their approaches for the criteria were compared with the results of experiments at the host company. These comparisons were presented in Table 39 and Table 40 in the Discussion Chapter and the similarities and differences were noted. An important caveat to any conclusions drawn was the limited scope of the experiments, often involving a single case, and all at one company. The experimental findings supporting the claims in literature will not be discussed again here to avoid repetition. Furthermore, these confirmations were less interesting than the situations when the experiments contradicted established views.

Bearing in mind the above caveats, the experiments contradicted the literature for the QM&S theme in two criteria, finding it was not *'usable at the early stage of planning'* due to the lack of reliable data (Section 5.4.21 Result 21), but was *'usable by managers with technical* *knowledge'* because of the simple GUI and computerised calculations (Section 5.4.10 Result 10). Perhaps controversially, literature claims that the Flowchart theme was '*usable by managers with technical knowledge'* were not supported by the experiment (Section 5.4.9 Result 9). While the format is easy to understand, completing it to enable specification of automated manufacturing systems required knowledge and experience of participants and larger groups.

QM&S approaches were the least applicable to ETO products in literature due to the difficulty in configuring a model to enable bespoke designs to be simulated. This was confirmed in the experiment but could be mitigated to some extent using templates. However, the experiment found DDA to be the least effective for ETO products due to the huge number of options and variables making their development and use unwieldy (Section 5.4.20 Result 20).

6.4 Limitations and future work

This research was limited by several factors that influence the generalisability of the findings. The data gathering and experiments were conducted in one host company, limiting its applicability to other businesses. Another restriction was time and resources available to test theories empirically in the host company. The research was over a period of two years providing limited longitudinal possibilities. To improve generalisation future work could include case studies, interviews or surveys at other small businesses and investigation of the host company for a longer time.

A major weakness of the AHP analysis performed was that pairwise comparisons were completed solely by the author, introducing a significant possibility of mistakes or bias. This was mitigated by basing the decisions on the results of the literature review for the literature AHP, and using comments from engineers and managers along with the experimental evidence for the AHP of the experiments. Other ways of ranking criteria would be to use a survey (Appendix A) as was attempted but abandoned due to limited resources and the quantitative nature not fitting with the research methods, or through one or more focus groups/workshops with industry professionals. This could be considered for future work.

The themes have some overlap with each other in literature, which could cause a paper to be wrongly categorised in one theme or another. Additionally, QM&S could be subdivided further as it incorporates a variety of approaches and this would change not only the rankings of the new sub-themes but could affect the ranking of the other three main themes due to increasing the number of pairwise comparisons and introducing the possibility of rank reversal as described in Section 3.5.3 Analytical hierarchy process. Some of the criteria, although not mutually exclusive are competing for resources, for example rapid application and considering not just the financial costs and benefits; as the more detailed an approach is the slower it is likely to be. Some are complimentary such as being usable by managers with technical knowledge and for small businesses as ease of use and low resource cost often correlate. This can cause problems for AHP where the categories should ideally be mutually exclusive. However, in the real world of operations management categories often overlap or have competing or complementary properties.

The necessity for input from multiple stakeholders in the flowchart experiment required several meetings and numerous emails to acquire data, which was a time consuming process. None of the papers in the literature review mentioned this and it could be inferred that they did not suffer this issue or did not include it in their findings. In either case, this could indicate further investigation in the future would be beneficial. Additionally, the team that helped to construct the flowchart were experienced in the automation field and a less knowledgeable team may have struggled, which could be the subject of future study.

Combining approaches from different themes could be a way to overcome the weaknesses of one approach using the strengths of another. For example combining approaches from consultancy with QM&S to address the inclusion of intangibles or a flowchart specifically for consideration of these intangibles could be produced as part of the process, perhaps as a first step to inform choices in the modelling of tangible factors and this could be another subject for future work. Costs and benefits other than financial could be further investigated using a customer survey that includes the intangible benefits they may achieve by implementing automation such as publicity from being a perceived market leader. Finally, although the proliferation of databases available through an internet browser makes comparing options time consuming, a structured approach or procedure to guide the user could ensure exhaustive and consistent consideration of alternative options, which could form the basis of future work.

6.5 Overall conclusions

This Chapter has examined the contribution to knowledge from several perspectives and the answers to the research questions posited at the beginning of the thesis. The six identified criteria were useful for comparing existing approaches and defining the required qualities of future strategies to specify automation. The four themes of research in existing literature had different qualities, strengths and weaknesses, although some overlap between them was observed. None of the themes reviewed completely satisfied all six criteria for an approach to specify automated manufacturing systems (AMS) either in literature or experimentally. For this reason, a hybrid approach may be the best option using the best features from each theme and an outline of this is illustrated in Figure 38.

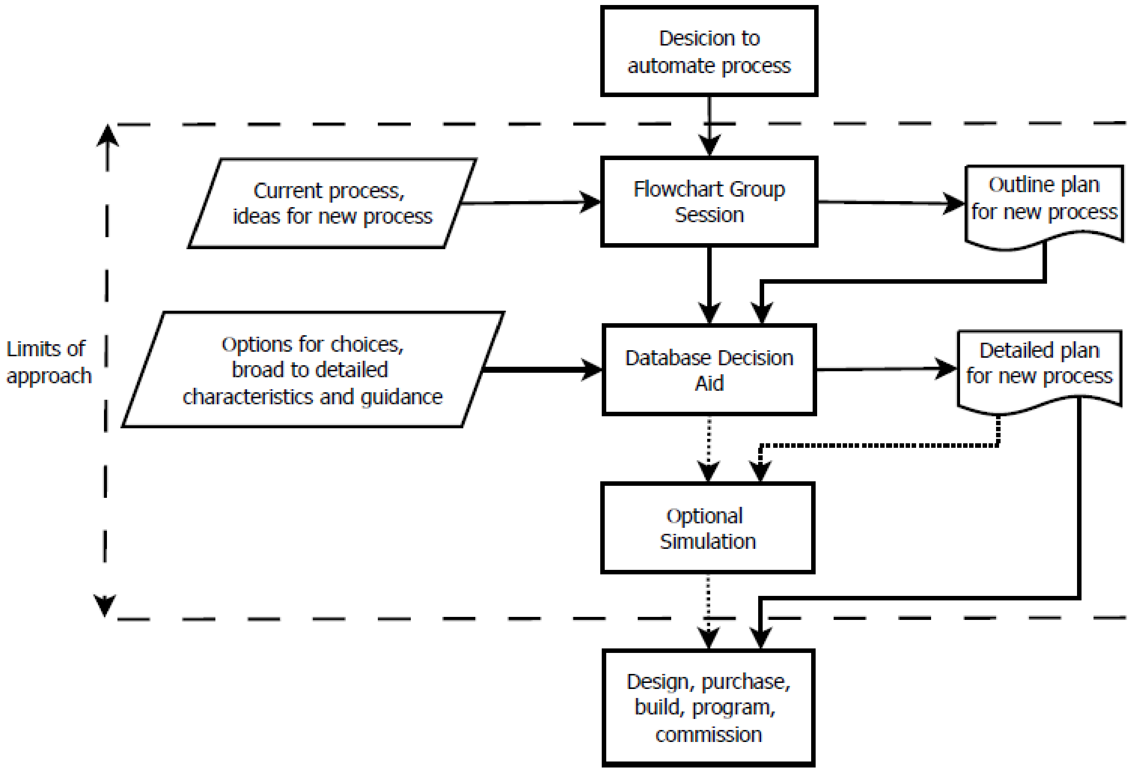


Figure 38: Outline of possible automated production system specification process.

A useful first step would be a group flowchart meeting to gather ideas and information due to its usability at the early stage of planning (Section 5.4.22 Result 22). This would avoid the assumptions required for QM&S (Section 5.4.21 Result 21) and the restrictive structure of DDA (Section 5.4.23 Result 23). Internal stakeholders could be supplemented by bringing in an external subject matter expert to assist, although an awareness of their motivations would be necessary, for example selling their own product. The flowchart would illustrate the current state of the existing process and possible improvements or set out the proposed production process for a new product. Diagrams could consist of the production actions required, helping those involved to compare ideas with inexact information, while at the same time reducing the number choices required in the next stage of planning.

Informed by the plan from the flowchart, a second stage could use a structured DDA to provide information and guide decision makers in selecting methods of completing the desired production actions (Section 5.4.13 Result 13). These choices could begin with broad decisions, for example between flexible or hard automation and refine these down to a desired level of detail. Each decision would be informed by providing the important qualities and specifications for comparison and selection based on balancing cost, performance and utility. The speed and ease of use of the approach could be increased by using a good graphical user interface (Section 5.4.5 Result 5). The output of this stage would be a model of the proposed production system that could be specified down to the component level. This model could then be simulated and compared with alternatives in an optional third stage or used directly in ordering, building, programming and commissioning the AMS.

The optional third stage could test options using simulation of the model made possible by the detailed specification of the previous stage. This could include some randomness such as machine breakdown to increase realism and would increase confidence in a design to assist with approval of high cost investments. Simulating graphically may also reveal issues that were previously unforeseen such as physical collision or incompatibility of components. However, if the previous stage had produced a detailed enough model all of the important characteristics of the machine will already be available for comparison without the need for simulation.

As use of automation for production processes increases, those that are easily modified or provide the highest return on investment will already have been done. The remaining options will present returns that are more marginal and be more difficult to realise so the need for an approach to specify automation will increase further. It is hoped that this work will aid future researchers in designing suitable tools to assist planners in industry with this complex task. However, automation of every process should not be the goal of society as many people enjoy having work to do as long as they have some agency and are properly compensated. Perhaps with the increase in automation the balance of work will shift to working less hours, freeing up time for families to spend with each other and improving the wellbeing of future generations.

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Appendix A

Survey 1

Manufacturing Automation

1. Information for use

1. I have read and understood the above information. I understand that I can withdraw my information for up to one month. I understand that my anonymity will be maintained by the researcher and it will not be possible to identify me in any publications.				
			Response Percent	**Response Total**
1	Yes		100.00%	16
2	No		0.00%	0
			answered	16
			skipped	0

2. Page 2

2. The method should be quick to apply.				
			Response Percent	**Response Total**
1	Strongly Disagree		0.00%	0
2	Disagree		0.00%	0

2. The method should be quick to apply.				
			Response Percent	Response Total
3	Neutral		20.00%	3
4	Agree		53.33%	8
5	Strongly Agree		26.67%	4
			answered	15
			skipped	1

3. The method should be simple to use and not require specialist knowledge or training.				
			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		20.00%	3
3	Neutral		6.67%	1
4	Agree		40.00%	6
5	Strongly Agree		33.33%	5
			answered	15
			skipped	1

4. The method should consider not just the financial cost and benefits.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		6.67%	1
3	Neutral		6.67%	1
4	Agree		60.00%	9
5	Strongly Agree		26.67%	4
			answered	15
			skipped	1

5. The method should justify the specification over a two year ROI period.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		6.67%	1
3	Neutral		40.00%	6
4	Agree		46.67%	7
5	Strongly Agree		6.67%	1
			answered	15
			skipped	1

6. The method should be targeted towards small to medium enterprises.

		Response Percent	Response Total
1	Strongly Disagree	0.00%	0
2	Disagree	13.33%	2
3	Neutral	20.00%	3
4	Agree	53.33%	8
5	Strongly Agree	13.33%	2
		answered	15
		skipped	1

7. The method should be targeted towards engineer to order products.

		Response Percent	Response Total
1	Strongly Disagree	0.00%	0
2	Disagree	6.67%	1
3	Neutral	40.00%	6
4	Agree	53.33%	8
5	Strongly Agree	0.00%	0
		answered	15
		skipped	1

8. The method should be useful to the manufacturing industry.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		0.00%	0
3	Neutral		0.00%	0
4	Agree		53.33%	8
5	Strongly Agree		46.67%	7
			answered	15
			skipped	1

9. The method should be unbiased in choosing between different technology options.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		0.00%	0
3	Neutral		20.00%	3
4	Agree		46.67%	7
5	Strongly Agree		33.33%	5
			answered	15
			skipped	1

10. The method should have KPI's to evaluate each step.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		0.00%	0
3	Neutral		26.67%	4
4	Agree		46.67%	7
5	Strongly Agree		26.67%	4
			answered	15
			skipped	1

11. The method should be usable at the early stage of planning.

			Response Percent	Response Total
1	Strongly Disagree		0.00%	0
2	Disagree		6.67%	1
3	Neutral		33.33%	5
4	Agree		26.67%	4
5	Strongly Agree		33.33%	5
			answered	15
			skipped	1

12. Are there any other criteria you think are important?				
			Response Percent	Response Total
1	Open-Ended Question		100.00%	2
1	23/11/2019 15:53 PM ID: 131419421	Impact of the technology on the environment. effect of technology on job prospects		
2	24/11/2019 09:38 AM ID: 131431667	The method should have some kind of warning system or means of highlighting potential problems and issues early. As well as capturing them this could give a method for tempering the scope and expectations, or so they can be adjusted accoringly. The method should have simple visual and/or statistical outputs as an option for the client to use in justification.		
			answered	2
			skipped	14

Survey 2

Method to assist specification of manufacturing automation.

1. Information for use

Please read this information sheet carefully before deciding whether you would like to take part in this research project.

This research is being carried out as part of a collaboration between Plymouth University and Oakmount Control Systems Ltd. The aim of this research is to develop a method to help companies to implement automation in their processes. The method will do this by detailing which data to gather and guiding the user to create a specification for an automated solution that can be justified financially.

The purpose of this survey is to find out which criteria are most important to industry. Participation is voluntary – it is up to you whether you take part. Your anonymity will be maintained by the researcher and your data will be used in accordance with GDPR regulations.

As an incentive to share your views each respondent can receive a free copy of the completed method. The survey should take less than 5 minutes to complete.

1. I have read and understood the above information. I understand that I can withdraw my information for up to one month. I understand that my anonymity will be maintained by the researcher and it will not be possible to identify me in any publications.

☐ Yes

☐ No

2. When thinking about the use of a method to specify automation, please rank the following choices in order of importance. (if completing on a mobile device choices must be dragged instead of entering the rank number)

Tested and validated in industry.	☐
Quick to use.	☐
Simple to use and not requiring specialist knowledge or training.	☐

Any other factors you think are important?

3. When thinking about where the method to specify automation should be targeted, please rank the following choices in order of importance. (if completing on a mobile device choices must be dragged instead of entering the rank number)

Early stage of planning.

Small to medium enterprises.

Engineer to order products (products that are produced to customer specifications and each one is different).

Are there any other areas you think are important to target?

4. When thinking about the data that needs to be gathered when specifying automation, please rank the following choices in order of importance.

Current cycle time.

Current cost per product.

Current process steps.

Not sure about this question.

5. When thinking about financial justification provided by the method for an automation project, please rank the following choices in order of importance. (if completing on a mobile device choices must be dragged instead of entering the rank number)

Provides detailed and accurate cost for the project.

Justifies the automation project over a two year return on investment period.

Provides an overall estimate of cost for the project.

Considers not just the financial costs and benefits but also intangibles such as customer perception.

Are there any other financial considerations you think are important?

6. When thinking about other features of the method to specify automation, please rank the following choices in order of importance. (if completing on a mobile device choices must be dragged instead of entering the rank number)

Unbiased in choosing between different technology options.

Has Key Performance Indicators to evaluate each step.

Are there any other features that you think are important?

7. Are there any other criteria you think are important?

8. If you would like to receive a free copy of the method at the end of the research please leave your email address below.

Appendix B

Table 43: Reviewed literature coded by theme.

Theme / Author	QM&S	DDA	Flowchart modelling	Consultation
Adrodegari et al. (2015)				X
Afy-Shararah and Rich (2018)				
Agyapong-Kodua et al. (2013, 2014)			X	
Alvarez et al. (2018)				
Anand and Delios (2002)				
Ang (1999)			X	
Asawachatroj et al. (2012)		X		
Back et al. (2010)				
Baines (2014)				X
Baldwin et al. (2014)		X		
Baxter et al. (2017)				
Benesova and Tupa (2017)				
Bernedixen et al. (2013)	X			
Biege et al. (2012)			X	
Blackwell et al. (2017)				
Bloomfield et al. (2012)	X			
Bokrantz et al. (2018)	X			
Boothroyd (2005)	X			X

Boothroyd and Dewhirst (1983)		X		
Borgianni and Matt (2015, 2016)				
Bornschlegl et al. (2015)	X			
Bortolini et al. (2015)				
Boteanu et al. (2018)	X			
Boysen et al. (2009)				
Bradford (2000)				X
Buergin et al. (2017)				
Bukchin and Tzur (2000)	X			
Busogi et al. (2017)	X			
Cao et al. (2019)				
Cavalieri et al. (2004)	X			
Cavone et al. (2018)	X			
Chaharbaghi (1987)	X			
Chan, F.T.S. et al. (2001)				X
Chan, Kwong and Tsim (2001)	X			
Chen and Huang (2013)	X			
Chen and Small (1996)				X
Chen, Feng and Zhang (2003)	X			
Childe (1991)				X
Childe, Maull and Bennet (1994)				
Chui et al. (2017)				
Constantinescu, Francalanza and Matarazzo (2015)	X			
Cutting-Decelle et al. (2007)				
Dalenogare et al. (2018)				
Davidsson and Gustafsson (2011)				
De Felice et al. (2018a)				
De Felice et al. (2018b)			X	
Delgado-Maciel et al. (2018)				
Dinis-Carvalho et al. (2015)				

Dotoli et al. (2018)				
Dudas et al. (2014)	X			
Duflou and D'hondt (2011)				
Eduardo Pereira et al. (1996)				
Fantini et al. (2018)				
Farid and Ribeiro (2015)	X			
Farooq and Obrien (2012), (2015)				X
Fast-Berglund and Stahre (2013)			X	X
Fasth (2011)			X	X
Fasth et al. (2008)	X			
Ferrer et al. (2016)	X			
Fey and Rivin (2007)				
Fischer, Obst and Lee (2017)	X			
Fjodorova and Novic (2015)	X			
Frohm et al. (2008)			X	X
Fulton and Hon (2010)				X
Garretson et al. (2018)				
Gingele (2001)			X	
Gorlach and Wessel (2008)	X			
Goyal and Grover (2012)				
Greasley and Owen (2018)	X			
Gunasekarap and Ichimurab				
Guschinskaya et al. (2011)	X			
Hamzeh et al. (2018)		X		X
Hassmiller et al. (2017)				
Heilala, Helin and Montonen (2006)	X			
Herman, Pentek and Otto (2016)				
Hernández-Martinez et al. (2016)	X			
H'mida, Martin and Vernadat (2006)	X			
Hu and Zhou (2015)	X			
Jagstam and Klingstam (2002)	X			

Jung et al. (2017)			X	
Kaartinen, Pieska and Vahsoyrinki (2017)				X
Kagermann et al. (2013)				
Kaplin and Anderson (2007)	X			
Khan and Day (2002)				
Khodadadi (2018)				
Kianian, Kurdve and Andersson (2019)	X			
Kim and Lee (2013)	X			
Kolberg and Zuhlke (2015)				
Koren and Shpitalni (2010)	X			
Koren, Gu and Guo (2018)	X			
Krugh and Mears (2018)				
Kunica and Vranjes (1999)	X			
Kusiak (2018)				
Lager et al. (2017)				X
Larsen (1994)				X
Lechevalier et al. (2018)	X			
Lee et al. (2013)				
Lee et al. (2018)				
Lee, Bagheri and Kao (2015)				
Lentes et al. (2014)	X			
Leu et al. (2013)	X			
Liao et al. (2017)				
Lidberg, Pehrsson and Frantzen (2018)	X			
Lidberg, Pehrsson and Ng (2019)	X			
Lindholm and Johansen (2018)				
Lindstrom and Winroth (2010)				X
Liu (2007)				
Ljungkrantz, Fabian and Yuan (2010)				
Long, Zeiler and Bertsche (2016)	X			

Long, Zeiler and Bertsche (2018)	X			
Lorraine (2008)				
Lu (2017)				
Machado and Seabra (2012)				
Mahmood, K. et al. (2017)			X	
Maia, Alves and Leao (2015)				
Mann (2002)				
Maull and Childe (1993)				
Mazak and Huemer (2015)			X	
McGovern and Hicks (2006)				
McKinsey Global Institute (2018)				
Mclean et al. (2005)	X			
Meziani and Magalhaes (2009)				
Michalos, Makris and Mourtzis (2012)	X			
Mohammad et al. (2017)			X	
Nazarian, Ko and Wang (2010)	X			
Negahban and Smith (2014)	X			
Ng, Urenda and Svensson (2007)	X			
Oppelt, Wolf and Urbas (2015)	X			
Ordoobadi and Mulvaney (2001)				X
Parasuraman, Sheridan and Wickens (2000)				
Park and Li (2019)	X			
Park et al. (2017)				
Pastor and Ferrer (2009)				
Pehrsson, et al. (2015)				
Pehrsson, Ng and Bernedixen (2016)				
Pehrsson, Ng and Stockton (2013)	X			
Perera and Lyanage (2000)			X	
Petin et al. (2006)		X		
PTC Inc (2015)				X

Qin, Liu and Grosvenor (2016)				X
Qiu (2007)				
Qurashi (2000)			X	
Rahardjo and Yahya (2010)				X
Rahman and Mo (2010), (2012)			X	
Ramis et al. (2015)		X		
Ramis et al. (2016)				
Rauch, Matt and Dallasega (2016)				
Ribiero et al. (2016, 2017, 2018)	X			
Ridgeway (2014)	X			
Robertson et al. (1995)	X			
Roda, Macchi and Albanese (2019)				X
Rondini et al. (2017)				
Roshani and Giglio (2015)				
Rother and Shook (1999)			X	X
Roy et al. (2011)			X	
Rural Development Alberta (no date)				X
Saberi and Yusuff (2012)	X			
Salmi et al. (2015), (2018)	X			
Salmi et al. (2016)	X			
Sambasivarao and Deshmukh (1995)		X		
Sambasivarao and Deshmukh (1997)		X		
Sarachaga et al. (2019)			X	
Savoretti et al. (2017)		X		
Segal (2018)				
Šerifi et al. (2009)			X	
Seth et al. (2017)			X	
Shehabuddeen et al. (2006)	X			
Shrouf et al. (2014)				
Skoogh and Johansson (2008)	X			
Small and Chen (1997)	X			

Son (1991)	X			
Spedding and Sun (1999)	X			
Stähr, Englisch and Lanza (2018)				X
Stock and Seliger (2016)				
Sutherland and Baker (2007)				X
Swift and Booker (2013)	X			
Tan and Wong (2017)	X			
Taylor and Robinson (2006)				
Teufl and Hackenberg (2015)				X
Theorin et al. (2016)				
Thomas et al. (2008)				X
Thomassen, Sjobakk and Alfnes (2014)				X
Thomassen, Alfnes and Gran (2015)			X	X
Thompson (1995)				X
Turner et al. (2016)				
Vastag (2000)				
Verhagen et al. (2015)				
Wagner, Herrmann and Thiede (2017)				
Wang et al. (2018)				
Wang, Tang and Li (2010)			X	
Watson (2012)				
Weber-Jahnke and Stier (2009)	X			
Wehrmeister et al. (2014)			X	
Weyer et al. (2015)				
Wilkesmann and Wilkesmann (2018)				
Windmark et al. (2012)	X			
Winroth et al. (2006)		X		X
Wu and Zhou (2010)	X			
Wuest et al. (2016)	X			
Yadav and Jayswal (2018)	X			
Yasuda and Ge (2010)	X			

Zennaro et al. (2019)				
Zezulka et al. (2016)				
Zhang, D. et al. (2016)				
Zhang, J. and Agyapong-Kodua (2015)	X			
Zhang, Y. and Fuh (1998)	X			
Zhou et al. (2011)	X			
207	72	10	23	32

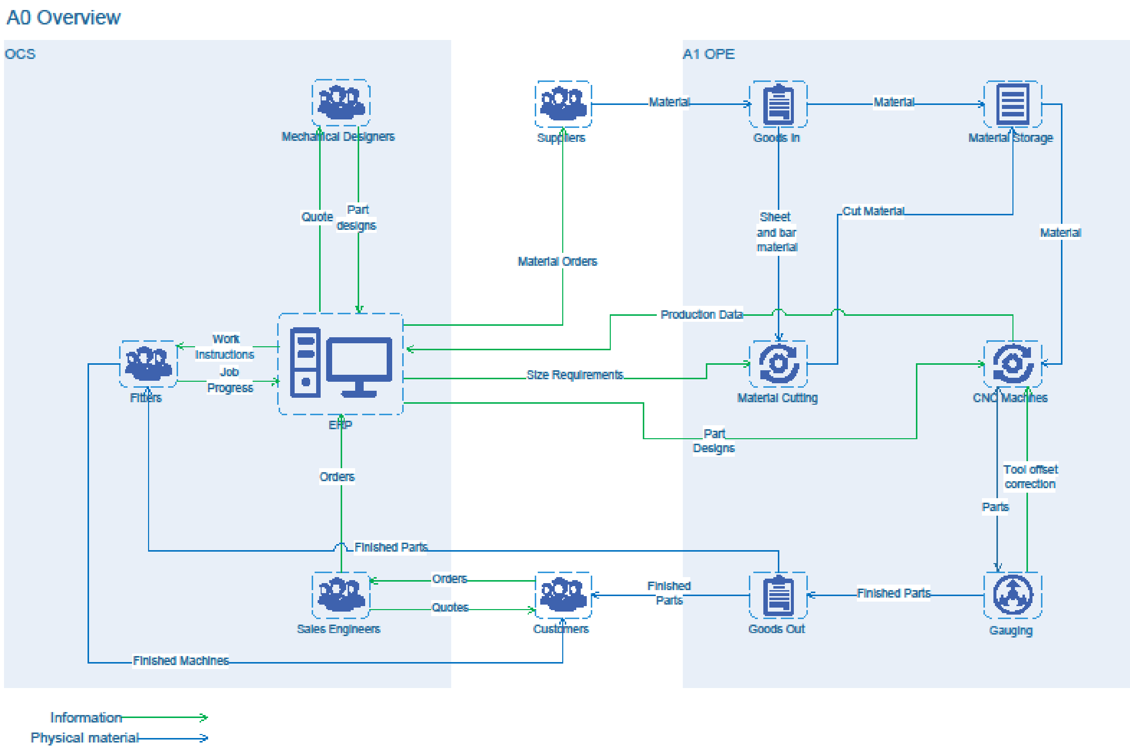


Figure 39: Full embeded interactive .pdf of the TO-BE flowchart

Table 44: Robot movement time experimental results to help create the cycle time estimation tool. Ratios were calculated from the median times to perform different movements e.g. Joint move vs Linear move.

Condition	Joint	Linear	No Z	Yes Z	No Obs	Med Obs	High Obs
Time (ms)	3912	5638	3912	7908	3912	5180	6901
	2180	6538	5638	7598	5638	6538	7392
	6901	7392	5180	5366	5937	5366	7908
	7598	7908	6538	7020	3934	7020	7598
	5366	7020	6901	5937	1971	6625	9347
	3934	5937	7392	3934	2866	7247	8463
	9347	8463	7959	9347	1965	3991	7959
	8221	7959	8221	8463	3299	3126	8221
	6625	7247	6625	4977	6399	4977	5307
	1971	2866	7247	3984	5644	3984	5366
	3126	3991	1971	5438	5750		5438
	5307	5366	2866	6366	6311		6366
	3984	4977	3991	1965			
	5438	6366	3126	3299			
	1965	3299	5307	5750			
	6399	5644	5366	6311			
	6311	5750	6399				
			5644				
Average	5210.882	6021.235	5571.278	5853.938	4468.833	5405.4	7188.833
Median	5366	5937	5641	5843.5	4786	5273	7495
Ratio		0.903823		0.89015		0.907643	0.638559

Appendix C

Experimental AHP

Pairwise Comparison of Themes for Rapid Application				
Themes evaluated pairwise				**Reasons**
QM&S	9	**DDA**	6	Both use computers to speed up use
QM&S	9	**Flowchart**	3	Flowchart required multiple meetings and communication over email
QM&S	9	**Consultancy**	4	Consultancy required multiple meetings and communication over email
DDA	6	**Flowchart**	3	Flowchart required multiple meetings and communication over email
DDA	6	**Consultancy**	4	Consultancy required multiple meetings and communication over email
Flowchart	3	**Consultancy**	4	Both required multiple meetings

AHP Matrix for Rapid Application				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	1.50	3.00	2.25
DDA	0.67	1.00	2.00	1.50
Flowchart	0.33	0.50	1.00	0.75
Consultancy	0.44	0.67	1.33	1.00
Sum	2.44	3.67	7.33	5.50

Normalised AHP Matrix for Rapid Application						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.409	0.409	0.409	0.409	0.409	0.110
DDA	0.273	0.273	0.273	0.273	0.273	0.073
Flowchart	0.136	0.136	0.136	0.136	0.136	0.037
Consultancy	0.182	0.182	0.182	0.182	0.182	0.049

Rapid Application Consistency Ratio	
Criteria Priority =	0.27
Max Eigen =	4.00
CI =	0.00
RI=	0.90
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Usable by Managers				
Themes evaluated pairwise				**Reasons**
QM&S	7	**DDA**	7	DDA in Excel is easy to understand. QM&S required training
QM&S	7	**Flowchart**	4	Flowcharts are graphical and easy to understand
QM&S	7	**Consultancy**	3	Consultancy requires expert knowledge to complete, whereas QM&S can be data entry once complete
DDA	7	**Flowchart**	4	Flowchart requires more creativity than looking up options in a DDA
DDA	7	**Consultancy**	3	Consultancy requires expert knowledge to complete, whereas DDA is just looking up values
Flowchart	4	**Consultancy**	3	Consultancy requires expert knowledge to complete, whereas flowchart is easy to understand

AHP Matrix for Usable by Managers

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	1.00	1.75	2.33
DDA	1.00	1.00	1.75	2.33
Flowchart	0.57	0.57	1.00	1.33
Consultancy	0.43	0.43	0.75	1.00
Sum	3.00	3.00	5.25	7.00

Normalised AHP Matrix for Usable by Managers						
Normalised	QM&S	DDA	Flowchart	Consultancy	Local Priority	Global Priority
QM&S	0.333	0.333	0.333	0.333	0.333	0.086
DDA	0.333	0.333	0.333	0.333	0.333	0.086
Flowchart	0.190	0.190	0.190	0.190	0.190	0.049
Consultancy	0.143	0.143	0.143	0.143	0.143	0.037

Usable by Managers Consistency Ratio	
Criteria Priority =	0.26
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Not Just Financial				
Themes evaluated pairwise				**Reasons**
QM&S	1	**DDA**	9	DDA can contain stats that encompass every benefit of the option, whereas the QM&S done only takes into account cycle time
QM&S	1	**Flowchart**	1	Flowchart could indicate areas of interest but does not have any financial calculations similarly to QM&S
QM&S	1	**Consultancy**	8	Consultancy can consider all options, QM&S doesn't even calculate all the financial options
DDA	9	**Flowchart**	1	DDA can contain stats that encompass every benefit of the option, whereas flowcharts struggle with quantifying details without making them too detailed - can be done with multilayers
DDA	9	**Consultancy**	8	Consultancy has tools to consider financial and non-financial factors through discussions, DDA is limited by the amount of data input
Flowchart	1	**Consultancy**	8	Flowchart does not include financial details except some calculate cycle times, consultancy tools can include many financial calculations

AHP Matrix for Not Just Financial				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	0.11	1.00	0.13
DDA	9.00	1.00	9.00	1.13
Flowchart	1.00	0.11	1.00	0.13
Consultancy	8.00	0.89	8.00	1.00
Sum	19.00	2.11	19.00	2.38

Normalised AHP Matrix for Not Just Financial						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.053	0.053	0.053	0.053	0.053	0.015
DDA	0.474	0.474	0.474	0.474	0.474	0.132
Flowchart	0.053	0.053	0.053	0.053	0.053	0.015
Consultancy	0.421	0.421	0.421	0.421	0.421	0.117

Not Just Financial Consistency Ratio	
Criteria Priority =	0.28
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Small business/Resources				
Themes evaluated pairwise				**Reasons**
QM&S	3	**DDA**	6	DDA in Excel is easy to understand but needs a lot of resources to produce. QM&S required training
QM&S	3	**Flowchart**	7	Flowcharts are graphical and easy to understand and can be done with post-its, QM&S requires software and training
QM&S	3	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas QM&S can be data entry once complete
DDA	6	**Flowchart**	7	Flowchart requires some creativity but less effort than looking up options in a DDA
DDA	6	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas DDA is just looking up values
Flowchart	7	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas flowchart is easy to understand

AHP Matrix for Small business/Resources

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	0.50	0.43	0.50
DDA	2.00	1.00	0.86	1.00
Flowchart	2.33	1.17	1.00	1.17
Consultancy	2.00	1.00	0.86	1.00
Sum	7.33	3.67	3.14	3.67

Normalised AHP Matrix for Small business/Resources

Normalised	QM&S	DDA	Flowchart	Consultancy	Local Priority	Global Priority
QM&S	0.136	0.136	0.136	0.136	0.136	0.009
DDA	0.273	0.273	0.273	0.273	0.273	0.018
Flowchart	0.318	0.318	0.318	0.318	0.318	0.021
Consultancy	0.273	0.273	0.273	0.273	0.273	0.018

Small business/Resources	
Consistency Ratio	
Criteria Priority =	0.06
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for ETO

Themes evaluated pairwise				Reasons
QM&S	2	**DDA**	1	QM&S can be adapted from a template to cover a range of ETO products, DDA can cover common components but there is no point entering one off parts
QM&S	2	**Flowchart**	9	Flowcharts are more adaptable and flexible than QM&S which requires more configuration and data entry.
QM&S	2	**Consultancy**	7	Consultancy tools can be generalised to cover many ETO situations, QM&S would take longer to adapt
DDA	1	**Flowchart**	9	Flowchart flexible, DDA inflexible
DDA	1	**Consultancy**	7	Consultancy tools can be generalised to cover many ETO situations, DDA cannot cover every possible component easily
Flowchart	9	**Consultancy**	7	Both are similarly flexible

AHP Matrix for ETO

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	2.00	0.22	0.29
DDA	0.50	1.00	0.11	0.14
Flowchart	4.50	9.00	1.00	1.29
Consultancy	3.50	7.00	0.78	1.00
Sum	9.50	19.00	2.11	2.71

Normalised AHP Matrix for ETO						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.105	0.105	0.105	0.105	0.105	0.003
DDA	0.053	0.053	0.053	0.053	0.053	0.002
Flowchart	0.474	0.474	0.474	0.474	0.474	0.016
Consultancy	0.368	0.368	0.368	0.368	0.368	0.012

ETO Consistency Ratio	
Criteria Priority =	0.03
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Early Stage				
Themes evaluated pairwise				**Reasons**
QM&S	2	**DDA**	6	DDA can provide the information early on to help make decisions, QM&S relies on data that is often incomplete
QM&S	2	**Flowchart**	9	Flowcharts allow the expansion of ideas without necessarily having all information available, QM&S has strict data requirements to be able to run
QM&S	2	**Consultancy**	7	Consultancy can begin with little information and gather it during the process, QM&S requires the information to be available and accurate
DDA	6	**Flowchart**	9	Flowchart can be used to brainstorm ideas, DDA can provide information to assist planning
DDA	6	**Consultancy**	7	Consultancy provides a structured way to gain information and use it to plan, DDA only provides the data
Flowchart	9	**Consultancy**	7	Both are great for brainstorming and gaining information to begin planning

AHP Matrix for Early Stage				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	0.33	0.22	0.29
DDA	3.00	1.00	0.67	0.86
Flowchart	4.50	1.50	1.00	1.29
Consultancy	3.50	1.17	0.78	1.00
Sum	12.00	4.00	2.67	3.43

Normalised AHP Matrix for Early Stage						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.083	0.083	0.083	0.083	0.083	0.008
DDA	0.250	0.250	0.250	0.250	0.250	0.025
Flowchart	0.375	0.375	0.375	0.375	0.375	0.037
Consultancy	0.292	0.292	0.292	0.292	0.292	0.029

Early Stage Consistency Ratio	
Criteria Priority =	0.10
Max Eigen =	4.00
CI =	0.00
RI=	0.9
Consistency Ratio =	0.00

Literature review AHP

Pairwise Comparison of Themes for Rapid Application				
Themes evaluated pairwise				**Reasons**
QM&S	1.5	**DDA**	1	Both use computers to speed up use
QM&S	5	**Flowchart**	1	Flowchart required multiple meetings and communication over email
QM&S	7	**Consultancy**	1	Consultancy required multiple meetings and communication over email
DDA	3	**Flowchart**	1	Flowchart required multiple meetings and communication over email
DDA	5	**Consultancy**	1	Consultancy required multiple meetings and communication over email
Flowchart	3	**Consultancy**	1	Both required multiple meetings

AHP Matrix for Rapid Application				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	1.13	1.13	3.00
DDA	0.89	1.00	1.00	2.67
Flowchart	0.89	1.00	1.00	2.67
Consultancy	0.33	0.37	0.37	1.00
Sum	3.11	3.50	3.50	9.34

Normalised AHP Matrix for Rapid Application						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.321	0.321	0.321	0.321	0.321	0.086
DDA	0.286	0.286	0.286	0.286	0.286	0.077
Flowchart	0.286	0.286	0.286	0.286	0.286	0.077
Consultancy	0.107	0.107	0.107	0.107	0.107	0.029

Rapid Application	
Consistency Ratio	
Criteria Priority =	0.27
Max Eigen =	4.00
CI =	0.00
RI=	0.90
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Usable by Managers

Themes evaluated pairwise				Reasons
QM&S	1	**DDA**	6	DDA in Excel is easy to understand. QM&S required training
QM&S	1	**Flowchart**	8	Flowcharts are graphical and easy to understand
QM&S	1	**Consultancy**	1	Consultancy requires expert knowledge to complete, whereas QM&S can be data entry once complete
DDA	6	**Flowchart**	8	Flowchart requires more creativity than looking up options in a DDA
DDA	6	**Consultancy**	1	Consultancy requires expert knowledge to complete, whereas DDA is just looking up values
Flowchart	8	**Consultancy**	1	Consultancy requires expert knowledge to complete, whereas flowchart is easy to understand

AHP Matrix for Usable by Managers

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	0.17	0.13	1.00
DDA	6.00	1.00	0.75	6.00
Flowchart	8.00	1.33	1.00	8.00
Consultancy	1.00	0.17	0.13	1.00
Sum	16.00	2.67	2.00	16.00

Normalised AHP Matrix for Usable by Managers						
Normalised	QM&S	DDA	Flowchart	Consultancy	Local Priority	Global Priority
QM&S	0.063	0.063	0.063	0.063	0.063	0.016
DDA	0.375	0.375	0.375	0.375	0.375	0.096
Flowchart	0.500	0.500	0.500	0.500	0.500	0.129
Consultancy	0.063	0.063	0.063	0.063	0.063	0.016

Usable by Managers Consistency Ratio	
Criteria Priority =	0.26
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Not Just Financial				
Themes evaluated pairwise				**Reasons**
QM&S	1	**DDA**	9	DDA can contain stats that encompass every benefit of the option, whereas the QM&S done only takes into account cycle time
QM&S	1	**Flowchart**	5	Flowchart could indicate areas of interest but does not have any financial calculations similarly to QM&S
QM&S	1	**Consultancy**	9	Consultancy can consider all options, QM&S doesn't even calculate all the financial options
DDA	9	**Flowchart**	5	DDA can contain stats that encompass every benefit of the option, whereas flowcharts struggle with quantifying details without making them too detailed - can be done with multilayers
DDA	9	**Consultancy**	9	Consultancy has tools to consider financial and non-financial factors through discussions, DDA is limited by the amount of data input
Flowchart	5	**Consultancy**	9	Flowchart does not include financial details except some calculate cycle times, consultancy tools can include many financial calculations

AHP Matrix for Not Just Financial				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	0.11	0.20	0.11
DDA	9.00	1.00	1.80	1.00
Flowchart	5.00	0.56	1.00	0.56
Consultancy	9.00	1.00	1.80	1.00
Sum	24.00	2.67	4.80	2.67

Normalised AHP Matrix for Not Just Financial						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.042	0.042	0.042	0.042	0.042	0.012
DDA	0.375	0.375	0.375	0.375	0.375	0.105
Flowchart	0.208	0.208	0.208	0.208	0.208	0.058
Consultancy	0.375	0.375	0.375	0.375	0.375	0.105

Not Just Financial Consistency Ratio	
Criteria Priority =	0.28
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Small business/Resources

Themes evaluated pairwise				Reasons
QM&S	7	**DDA**	9	DDA in Excel is easy to understand but needs a lot of resources to produce. QM&S required training
QM&S	7	**Flowchart**	7	Flowcharts are graphical and easy to understand and can be done with post-its, QM&S requires software and training
QM&S	7	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas QM&S can be data entry once complete
DDA	9	**Flowchart**	7	Flowchart requires some creativity but less effort than looking up options in a DDA
DDA	9	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas DDA is just looking up values
Flowchart	7	**Consultancy**	6	Consultancy requires expert knowledge to complete, whereas flowchart is easy to understand

AHP Matrix for Small business/Resources

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	0.78	1.00	1.17
DDA	1.29	1.00	1.29	1.50
Flowchart	1.00	0.78	1.00	1.17
Consultancy	0.86	0.67	0.86	1.00
Sum	4.14	3.22	4.14	4.83

Normalised AHP Matrix for Small business/Resources

Normalised	QM&S	DDA	Flowchart	Consultancy	Local Priority	Global Priority
QM&S	0.241	0.241	0.241	0.241	0.241	0.016
DDA	0.310	0.310	0.310	0.310	0.310	0.020
Flowchart	0.241	0.241	0.241	0.241	0.241	0.016
Consultancy	0.207	0.207	0.207	0.207	0.207	0.013

Small business/Resources	
Consistency Ratio	
Criteria Priority =	0.06
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for ETO				
Themes evaluated pairwise				**Reasons**
QM&S	1	**DDA**	4	QM&S can be adapted from a template to cover a range of ETO products, DDA can cover common components but there is no point entering one off parts
QM&S	1	**Flowchart**	7	Flowcharts are more flexible than QM&S
QM&S	1	**Consultancy**	7	Consultancy tools can be generalised to cover many ETO situations, QM&S would take longer to adapt
DDA	4	**Flowchart**	7	Flowchart flexible, DDA inflexible
DDA	4	**Consultancy**	7	Consultancy tools can be generalised to cover many ETO situations, DDA cannot cover every possible component easily
Flowchart	7	**Consultancy**	7	Both are similarly flexible

AHP Matrix for ETO

	QM&S	DDA	Flowchart	Consultancy
QM&S	1.00	0.25	0.14	0.14
DDA	4.00	1.00	0.57	0.57
Flowchart	7.00	1.75	1.00	1.00
Consultancy	7.00	1.75	1.00	1.00
Sum	19.00	4.75	2.71	2.71

Normalised AHP Matrix for ETO						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.053	0.053	0.053	0.053	0.053	0.002
DDA	0.211	0.211	0.211	0.211	0.211	0.007
Flowchart	0.368	0.368	0.368	0.368	0.368	0.012
Consultancy	0.368	0.368	0.368	0.368	0.368	0.012

ETO Consistency Ratio	
Criteria Priority =	0.03
Max Eigen =	4
CI =	0
RI=	0.9
Consistency Ratio =	0.00

Pairwise Comparison of Themes for Early Stage				
Themes evaluated pairwise				**Reasons**
QM&S	9	**DDA**	6	DDA can provide the information early on to help make decisions, QM&S relies on data that is often incomplete
QM&S	9	**Flowchart**	8	Flowcharts allow the expansion of ideas without necessarily having all information available, QM&S has strict data requirements to be able to run
QM&S	9	**Consultancy**	8	Consultancy can begin with little information and gather it during the process, QM&S requires the information to be available and accurate
DDA	6	**Flowchart**	8	Flowchart can be used to brainstorm ideas, DDA can provide information to assist planning
DDA	6	**Consultancy**	8	Consultancy provides a structured way to gain information and use it to plan, DDA only provides the data
Flowchart	8	**Consultancy**	8	Both are great for brainstorming and gaining information to begin planning

AHP Matrix for Early Stage				
	QM&S	**DDA**	**Flowchart**	**Consultancy**
QM&S	1.00	1.50	1.13	1.13
DDA	0.67	1.00	0.75	0.75
Flowchart	0.89	1.33	1.00	1.00
Consultancy	0.89	1.33	1.00	1.00
Sum	3.44	5.17	3.88	3.88

Normalised AHP Matrix for Early Stage						
Normalised	**QM&S**	**DDA**	**Flowchart**	**Consultancy**	**Local Priority**	**Global Priority**
QM&S	0.290	0.290	0.290	0.290	0.290	0.029
DDA	0.194	0.194	0.194	0.194	0.194	0.019
Flowchart	0.258	0.258	0.258	0.258	0.258	0.025
Consultancy	0.258	0.258	0.258	0.258	0.258	0.025

Early Stage Consistency Ratio	
Criteria Priority =	0.10
Max Eigen =	4.00
CI =	0.00
RI=	0.9
Consistency Ratio =	0.00

Appendix D

Quantitative Modelling and Simulation Experiment Details

The literature surrounding the DREAM program set out the data required to run the simulation. Creating the data input fields was done in an excel spreadsheet with checkboxes, simple dropdown menu choices to restrict data input, and some free fields for label data as shown in Figure 40. These were organised into 'stations' representing an action in the production process, for example a press forming sheet metal or a label being applied. Initially, one linear production line could be modelled, up to six stations long but this was expanded to ten stations with three parallel branches available at each during testing. This improved representation of assembly line architecture, where multiple components are assembled into one product.

	Station 6A		Station 7A
Station type	Machine	Station type	Exit
Shared resource?	Operator_1	ared resource?	
Part No. (If Source)		Part No. (If Source)	
processingTime	4.5	processingTime	0.01
Predecessor 1	A	Predecessor 1	A
Predecessor 2	0	Predecessor 2	0
Predecessor 3	0	Predecessor 3	0
Parallel station?	Station 6B	Parallel station?	Station 7B
Station type	Machine	Station type	
Shared resource?		Shared resource?	
Part No. (If Source)		Part No. (If Source)	
processingTime	10	processingTime	
Predecessor 1	0	Predecessor 1	A
Predecessor 2	B	Predecessor 2	0
Predecessor 3	0	Predecessor 3	0

Figure 40: QM&S data entry form in Excel showing two parallel stations. 6A and 7A are in use and 6B and 7B are not in use.

To aid visualisation of the entered parameters, a graphical display of the entered data was presented (Figure 41). This was created through coding in Microsoft Visual Basic (VBA), which is an add-on for Excel and can be used to create Macros. Red boxes represent machine stations and green arrows are the route the product follows. The ‘source’ station type feeds the system with parts and may represent for example a bowl feeder. Machine stations perform an operation on the product that changes it in some way for example a press forming or punching a metal sheet. Assembly stations combine components into an assembly by putting one inside the other in the simulation, which approximates most combining actions. This could be a one-to-one ratio or multiple parts of one type could be fitted to the other part to simulate components such as bolts being inserted.

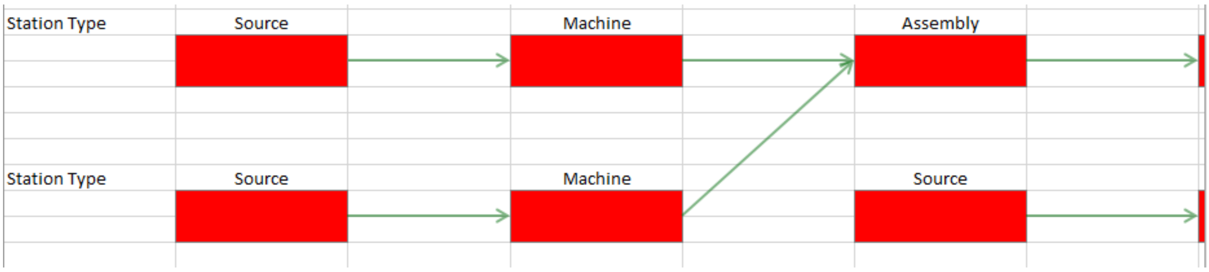


Figure 41: Graphical representation in the Excel data entry tool allowing users to confirm validity of entered information.

To input the entered data into the simulation package from the fields it had to be converted into .json format. This was done with further coding in VBA and required many iterations of trial and error to achieve the correct formatting to be accepted by the simulation package shown in Figure 42. The code cycles through a number of loops that check the entered data, add brackets and inverted commas and save the file as a .json. The simulation package is then triggered to read this file.

```
{
    "general": {
        "maxSimTime": 1440,
        "numberOfReplications": 1,
        "trace": "No"
    },
    "graph": {
        "edge": {
            "1": {
                "_class": "Dream.Edge",
                "destination": "Q1",
                "source": "S1"
            },
            "2": {
                "_class": "Dream.Edge",
                "destination": "M1",
                "source": "Q1"
            },
            "3": {
                "_class": "Dream.Edge",
                "destination": "E1",
                "source": "M1"
            }
        },
        "node": {
            "E1": {
                "_class": "Dream.Exit",
                "name": "Exit"
```


Figure 42: Example of the .json format required for data entry to the simulation package.

The code of the simulation itself was initially used as downloaded. However, as with the data entry form, through attempting to model assembly machines, new functionalities were discovered to be required and some of the code had to be modified. This again required much trial and error and was time consuming but beneficial. The code was adapted to allow combination of components into assemblies that were themselves combinable into the final product. The initial simulation only allowed insertion of 1-99 'Dream.Part' components into one 'Dream.Frame' container. The modified code made it possible to add 'Dream.Parts' to 'Dream.Frames' and then combine the 'Dream.Frames' with each other. This approximates a process such as assembling products and then packing them into a box.

The simulation package performed discrete event simulation, calculated the results and then exported them again in .json format. To parse this into user readable information more coding in VBA was required to present the data in a table in Excel (Figure 43). Simple excel functions were then used to turn this data into a set of bar graphs shown in Figure 44. The execution time depended on the complexity of the modelled system and the length of time to be simulated. It was typically under one minute, and for simpler systems with three or four stations only five to ten seconds. Exact times were not recorded as running a simulation for several minutes was still considered to be fast as a proportion of total time that included gathering data and inputting it. If the simulation had taken several hours, time to run would have been a more important consideration.

	A	B	C	D	E	F	G	H
1	Station	Working	Blocked	Waiting	Off-shift	Break	Setup	Failed
2	6A	14.22	0.00	83.84	0.00	0.00	0.00	1.94
3	5A	0.03	26.68	73.29				
4	2A	5.06	0.00	92.99	0.00	0.00	0.00	1.94
5	2B	9.81	0.00	88.25	0.00	0.00	0.00	1.94
6	3A	0.03	5.34	94.62				
7	4B	22.77	0.01	75.28	0.00	0.00	0.00	1.94
8	4A	5.38	0.00	92.68	0.00	0.00	0.00	1.94

Figure 43: Simulation output data table with time for different operations expressed as percentages of total machine time.

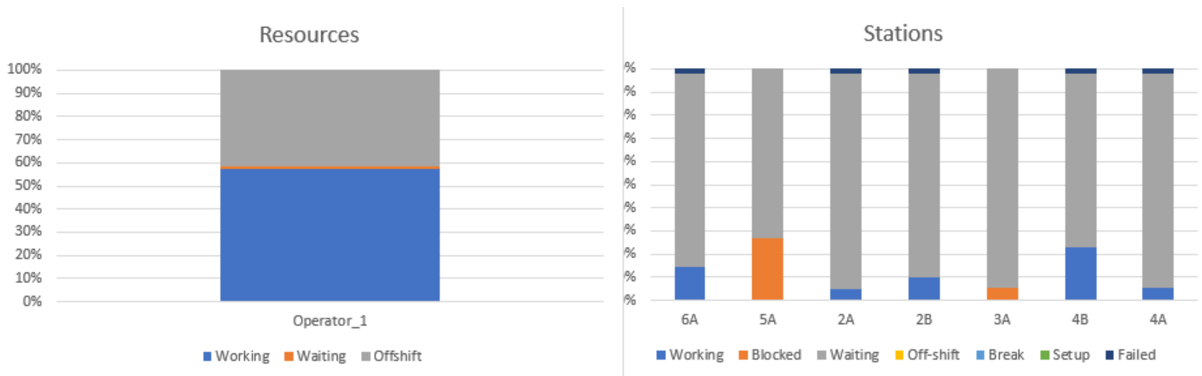


Figure 44: Graphical output of the QM&S spreadsheet showing the percentage of simulation time used by the resources (an operator) which are shared between machines and the machines themselves (Stations).

During construction of the approach, testing was done to confirm functionality of the code for a limited set of data. Once a working system was achieved that could produce correct and useful results a second round of testing was begun. This involved attempting to model industrial processes found on the popular "How It's Made" television program. Examples were the production of a crash helmet, a car seat, and bread rolls. When attempting to model these systems, deficiencies in the original modelling and simulation were identified. These were then addressed through further rounds of coding and functional testing. Some were relatively simple to resolve such as adding more stations, which required simple duplication. Others such as parallel processes required in depth structural changes to the data input fields, VBA code, .json data input structure, Python simulation package itself and data output presentation.

The second round of testing involved asking an untrained participant to use the modelling and simulation package after receiving only very basic information about its purpose. The participant was observed and the issues they encountered and questions they asked were recorded. These ranged from general questions about the purpose of the software and the reasons they would use it to very specific ones about what data to input into certain fields. They also managed to cause the software to crash by entering data that was unexpected. A post use interview was conducted and the author gathered opinions on how the approach could be improved for greater usability. The main point was that more general explanation was needed on what the system is for and how to begin using it. Another suggestion was to assist the user by indicating which cell to fill next, perhaps by highlighting it. However, this would have been too restrictive and would not allow the user freedom to model any production line. Findings from this testing were twofold. Firstly, more information was required in the user interface to assist them in use of the approach. This was implemented with tooltips to explain the functionality of the various fields (Figure 45). Secondly, further dropdown menus were introduced in fields to restrict user input as shown in Figure 46. This made the data entry process more robust to mistakes that could cause the program to crash due to incorrect inputs.

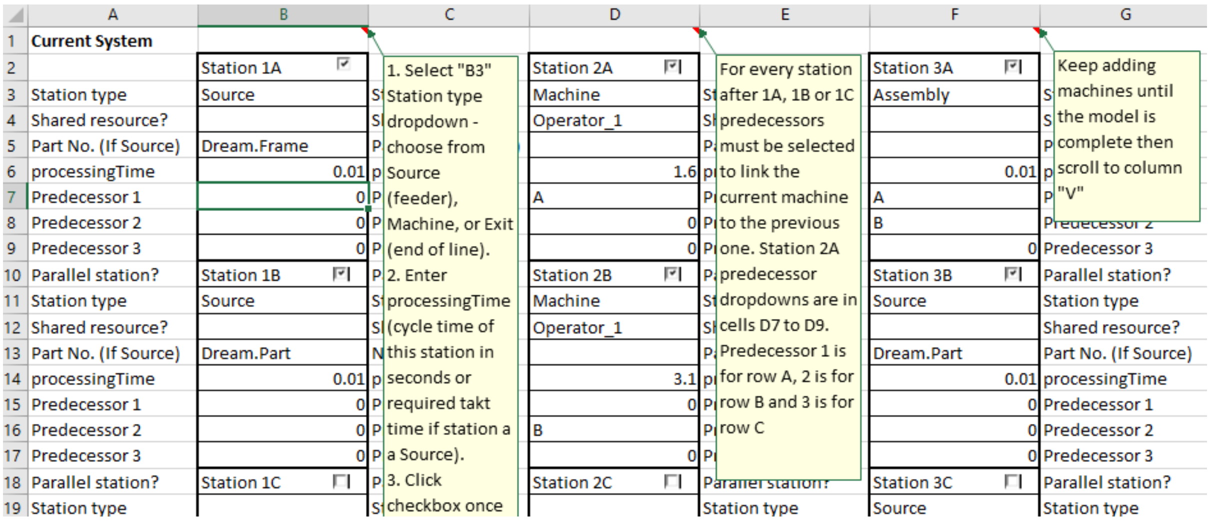


Figure 45: Data entry form in Excel showing the tooltips added to guide the user in use of the approach.

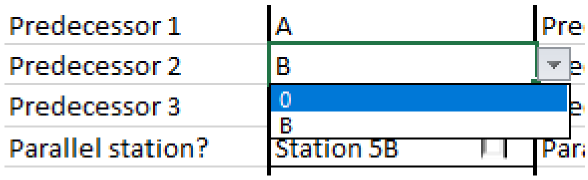


Figure 46: Example of a dropdown menu to restrict user input and make the data entry more robust.

Database Decision Aid experiment details

An alternative was sought to recording data on all available components to reduce the time and effort required to develop a database. One option was to look at only those components that had been used by the company already. Information on past projects was stored on a server in folders organised by project number, which ran consecutively in order of initiation. Each folder also had a short description containing the customer and machine name. This gave some clues as to which projects were relevant for this investigation. Many of the projects were excluded as they consisted of only the control panel, simple mechanical frames, or labour time to complete software or electrical maintenance. The number of eligible projects was also limited by time as those more than two years old were considered not representative of the current preferred methods of automation due to technological advances. These restrictions resulted in a list of 33 projects to be analysed.

Projects that were eligible were recorded in a spreadsheet along with their overall costs for material and labour (Figure 47). (Project numbers and costs have been obscured for confidentiality reasons.) These were again entered in a table to allow sorting alphabetically and numerically. The actions performed and costs were then broken down into separate columns to attempt calculation of approximate costs for each (Figure 48). Unfortunately, the quality of the data to be used was not good. Many actions and even whole projects did not have costs recorded. This caused many gaps in the table that, along with the small sample size and specialised nature of each project meant that only small numbers of prices for each action were available. Some of the actions also had highly variable prices adding to the unreliability of the data.

	A	B	C	D	E	F	G	H	I	
1	Job No	Quote No	Descriptio	Quote total (£k)	Quote Material (£k	Quote Labour (£k	Ratio	Electrical parts (£k	Mechanical parts (£k	Actions of machine
2	[redacted]		Spiral wrap machine	[redacted]						Wraps material around a mandr
3	[redacted]		Automated trimming of heatshink shapes	[redacted]						3 position rotary indexing machi
			Valve insert machine conveyor							

Figure 47: Screenshot of past projects database showing the project number, description, and overall cost of material and labour (project numbers and costs are redacted).

Contro	Cos	Display/ Interact	Cost17	Beacon	Cost18	Inspe	Cost	Detect	Cost3
PLC and control box w/ safety relay, power supply etc	5.745	HMI	2.6					Thermocouple, air flow meter,	0.682
PLC and control box w/ safety relay	2.9	HMI	0.9	Beacon	0.2			Laser sensor x2 and capacitive sensor x2	0.373

Figure 48: Screenshot of past projects database showing costs of components in thousands of GBP

The data are presented in Table 45 and graphically in Figure 49. The table shows many gaps in the samples. Some of these are due to the production action not being present in the project. Others are due to the data simply not being recorded. In addition to this, the range between maximum and minimum cost for some actions was very high. This could be attributed to the highly specialised and bespoke nature of each project requiring a wide range of capabilities and associated price levels. The experiment revealed the difficulty of using data from past projects to predict costs of future ones due to the huge variety of equipment from various manufacturers causing large variations in costs, and the lack of good data available. The number of suitable projects for analysis was only 34 due to the small size of the company making statistical analysis problematic due to sample size considerations.

Table 45: Collected data from 33 automation projects divided into the cost for each production action in thousands of GBP rounded to the nearest hundred. Shows the large spread in values between small and large projects and gaps in the data caused by data not being recorded

Project	Quote total (£k)	Quote Material (£k)	Quote Labour (£k)	Control	Display/ Interact	Detect	Feed	Guard	Change Temperature	Align/Orient	Test	Pick and Place	Singulate	Move
1	141.0	91.0	50.0	5.7	2.6	0.7		2.5		1.9				16.1
2	76.1	41.4	34.7	2.9	0.9	0.4								3.0
3	19.4	11.8	7.6											
4	2.3	1.3	1.0											
5	218.9	159.8	59.2	27			14.6	2.0			8.6	15	3.2	3.0
6	270.7	222.2	48.5	37.9			16.8	1.0		1.5		13.5	1.5	96.2
7	210.2	154.5	55.8	44.9			15.1	1.0		6.7		7.86	1.8	
8	843	679.5	163.5											
9	46.7	36.3	10.4									25.0		25.0
10	41.7	23.7	18.0	0.5						0.4		0.95	0.9	1.4
11	53.5	37.0	16.5	1.1	0.2	0.4								1.4
12	211.6	163.6	48.0	8.8			2.3							3.4
13	55.0	51.0	4.0											
14	21.4	11.4	10.0	5.105									0.25	0.2
15	17.5	7	10.5			0.44						2.2		
16	8.1	3.7	4.4		0.6									
17	13.3	9.7	3.6	1.5		0.1								4.8
18	40.0	31.0	9.0	0.9	0.3	0.2								10.8
19	569.0	419.0	150.0	29.0	3.6	8.2		42.1	31.8	0.3			1.7	51.5
20	1.7	1.2	0.5			0.1				0.2	0.1			
21	26.7	11.7	15.0	4.3	0.1	0.8		0.3				2.9		1.7
22	48.0	29.0	19.0	1.57	1.87	4.0		1.0						6.1
23	38.5	23.0	15.5	2.0	0.3			1.6			6.4			
24	115.0	63.0	52.0	4.2	1.2	2.5		3.5						5.6
25	135.0	105.0	30.0	13.5	1.15	2.5		0.3						3.0
26	111.0	76.0	35.0	3.9		0.2		0.3		0.5				2.1
27	371.0	326.0	45.0	17.2	4.3	2.1		12.4	24.4	12.1				23.7
28	51.8	46.9	4.9									45.3		
29	17.0	12.3	4.7			0.2								1.6
30	35.2	31.0	4.2	6.2	1.1	2.0								0.5
31	59.5	29.5	30.0											
32	172.0	107.0	65.0	9.7	3.0	0.65								9.9
33	34.0	27.5	6.5					0.9						
AVG	122.2	92.1	30.1	10.9	1.5	1.5	12.2	5.3	28.1	2.9	5.0	14.1	1.6	12.9
MED	51.8	36.3	16.5	5.1	1.1	0.7	14.8	1.0	28.1	1.0	6.4	10.7	1.6	3.4
MAX	843	679.5	163.5	44.9	4.3	8.2	16.8	42.1	31.8	12.1	8.6	45.3	3.2	96.2
MIN	1.67	1.17	0.5	0.5	0.1	0.1	2.3	0.3	24.4	0.2	0.1	1.0	0.3	0.2

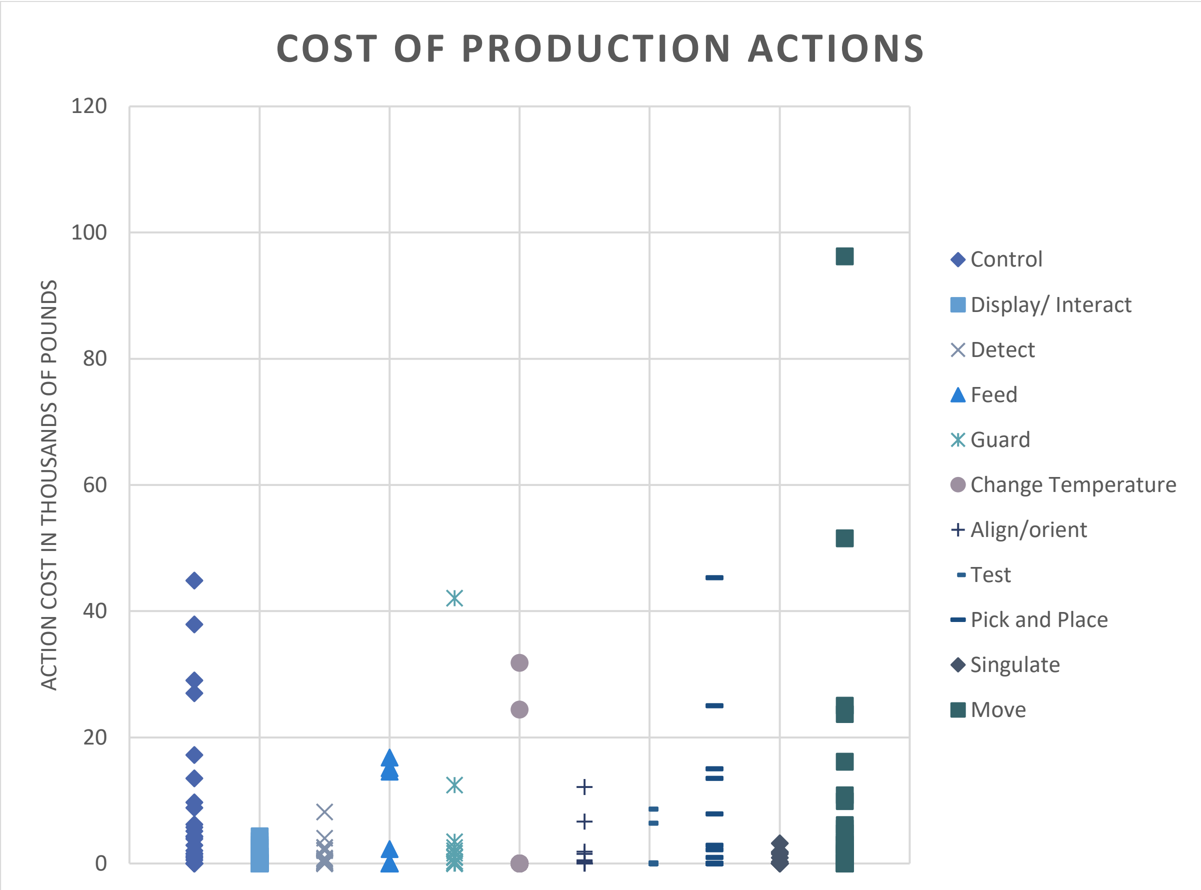


Figure 49: Graph showing the costs of different production actions in thousands of GBP across 33 projects in the host company.

As each action was not present in every project it is not possible to use their average or median costs to assess their relative proportions of total project cost. The figures for actual labour costs were not available and in any case would not be readily divisible into cost per production action. However, the proportion of labour to material costs from the quotes could be useful in predicting labour costs for future projects Figure 50. There is a discrepancy between the median of labour and material costs and the average. Due to the small sample size and widely spread data, the median is the more useful result to analyse. It shows that roughly two thirds of quoted costs relate to material and one third to labour. Again, the actual costs of these projects could not be analysed in the same way as the labour costs were unavailable and the material costs incomplete. However in future work the comparison of quoted and actual costs could yield valuable information to assist in future quotes.

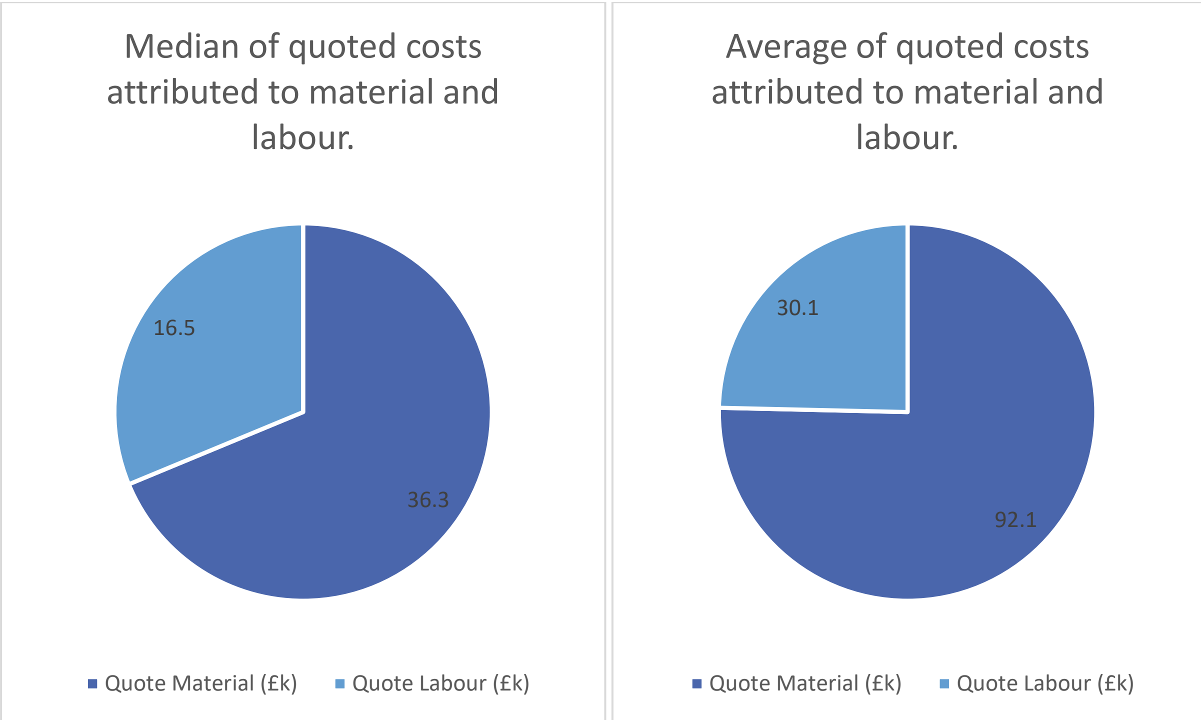


Figure 50: Quoted material and labour costs as a proportion of total project cost.

The cost is not the only consideration when choosing between different options for automation. To assist with decisions between components it would be useful for the database to contain information on other characteristics of each component. A limited attempt to incorporate these was trialled with a "tech database" which had a tab for each component containing a table of important features (Figure 51). Issues encountered were how to decide which information to include, where to get it, and how to overcome the problem of patchy data. The information to include was limited by what was available and an attempt was made to include only data that could be procured for every choice to reduce the possibility of bias. Data was retrieved from supplier datasheets, which were either downloaded from company websites or provided by sales representatives.

AGV Comparison	.omron.com/products/family/3664/spe		https://www.mobile-industrial	
	OMRON LD60	OMRON LD90	MiR100	MiR200
Price for starter kit (includes charging station, joystick)	£32,000	£32,000		
Price for additional units	£26,000	£26,000	£22,500 + VAT	£27,000 + VAT
Price for charger	Included	Included	£2,600	£2,600
Price for software (when using more than 1 robot)	£6,500	£6,500	£6,500	£6,500
Can plug in to charge?			Yes	Yes
Payload (kg)	60	90	100	200
Towing capacity (kg)				500
Speed (m/s)	1.8	1.35	1.5	1.1
Dimensions (Length x Width x Height) in mm	699x500x383	699x500x383	900x600x358	890x580x352
Running time without payload (hrs)	15	15	10	10
Charging time (hrs)	4 (1:5 ratio)	4 (1:5 ratio)	2 (0-80%)	2 (0-80%)
Positioning accuracy (mm)	100	100	100	50
Extra sensors Included			3D Camera	3D Camera
Extra sensors Not Included	Acuity - £8000	Acuity - £8000		

Figure 51: Excerpt from the tech database showing several automated guided vehicles (AGVs) along with important characteristics.

As with the spreadsheet of available automation components, the sheer number of different options made creating a complete database unrealistic so a subset of technologies was considered to test the tool. For this experiment, the database contained tabs for automated guided vehicles (AGVs), part feeders, cobots, 3D cameras, and a tab for sensors. One possible way to avoid unnecessary effort could be to enter information into the database only when there is a specific need. Each time an engineer chooses a component they could either look it up in the existing database or if it is not included add its details and options before selecting. Guidelines could be created for data entry such as comparing a minimum of three alternatives. In this way, the information in the database would be relevant to the needs of the company. However, it would be difficult to ensure the details contained in the database are kept up to date and engineers may not be happy to enter data.

Flowchart experiment details

Once a first draft of this top-level diagram was finished, it was presented to the project team and improvements and changes were discussed. The main further requirement was to incorporate more detail by expanding each area and to continue this deconstruction until the component level was reached. Figure 52 shows the expanded goods in and storage departments with greater detail about the methods to be employed such as automated vehicles and storage. These technologies were discovered through a mixture of research papers and sales materials of the products themselves and were discussed with the advisory group in a succession of meetings. The flowchart continued to drill down to the component level branching out and incorporating more and more detail (Figure 53). The full interactive pdf document is included in Figure 39 in Appendix B.

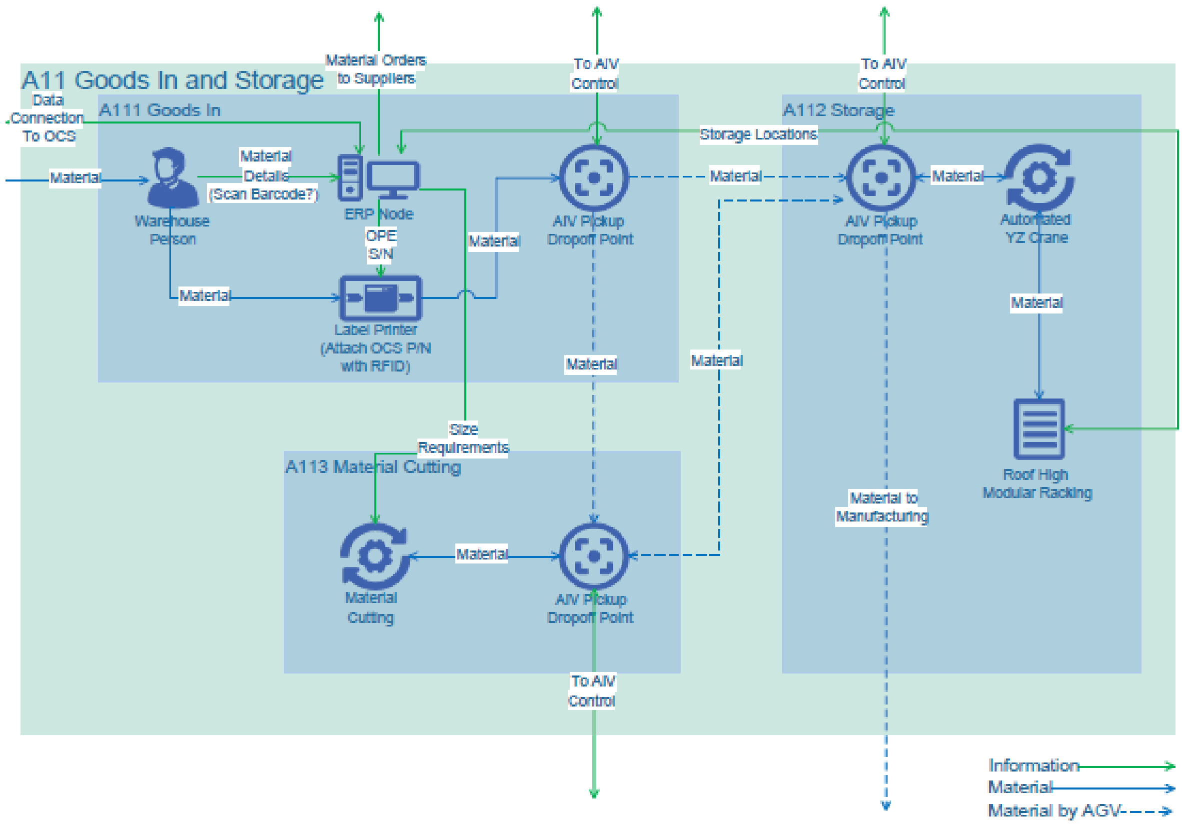


Figure 52: Expanded goods in and storage department flowchart.

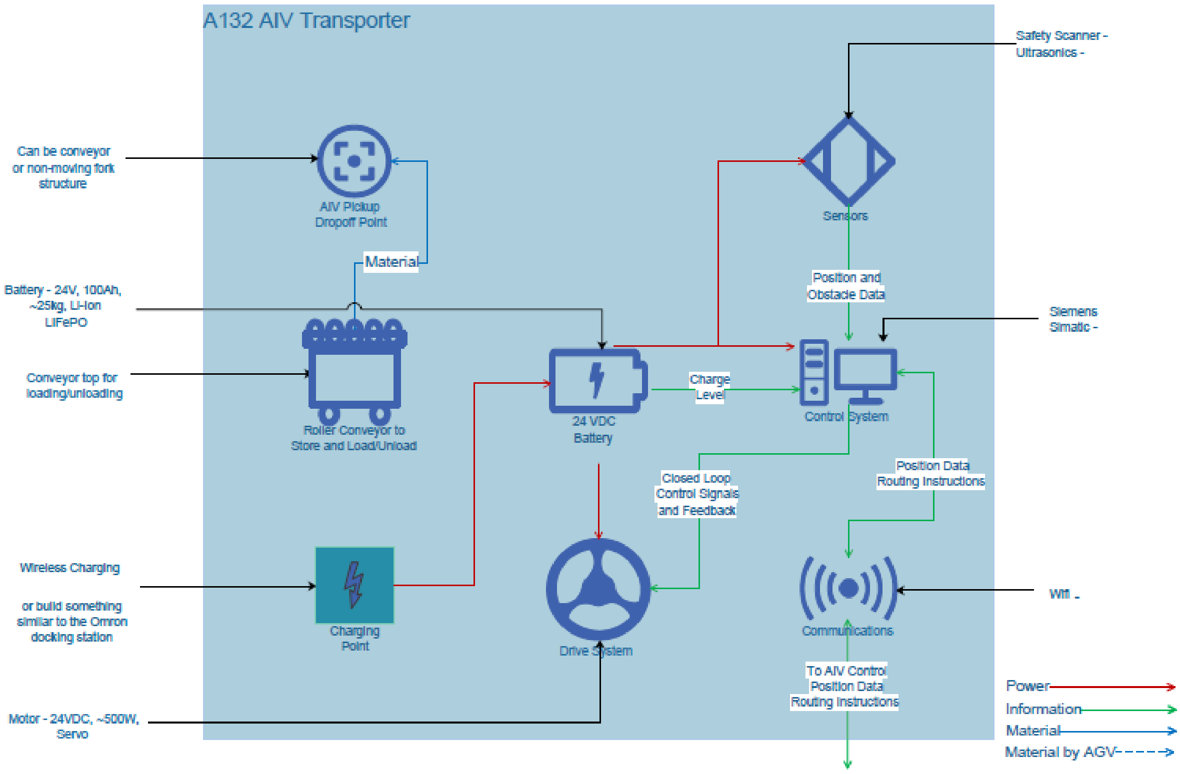


Figure 53: Component level diagram showing the automated intelligent vehicle used to transport material and finished parts throughout the workshop.

It was not until the TO-BE flowchart was shared with an external supplier of factory control software that the lack of an AS-IS diagram was brought up. With hindsight, it would have been more sensible to set out the current state (AS-IS) diagram first and then decide which changes could be made. As the information on current processes had already been gathered to construct the TO-BE diagram the AS-IS diagram was simple to construct (Figure 54). The external company only requested a top-level diagram to aid in proposing a software solution for interfacing the ERP with the machines. Unfortunately, the ERP system had not been fully implemented due to lack of time and motivation, which caused the whole proposal to be unworkable.

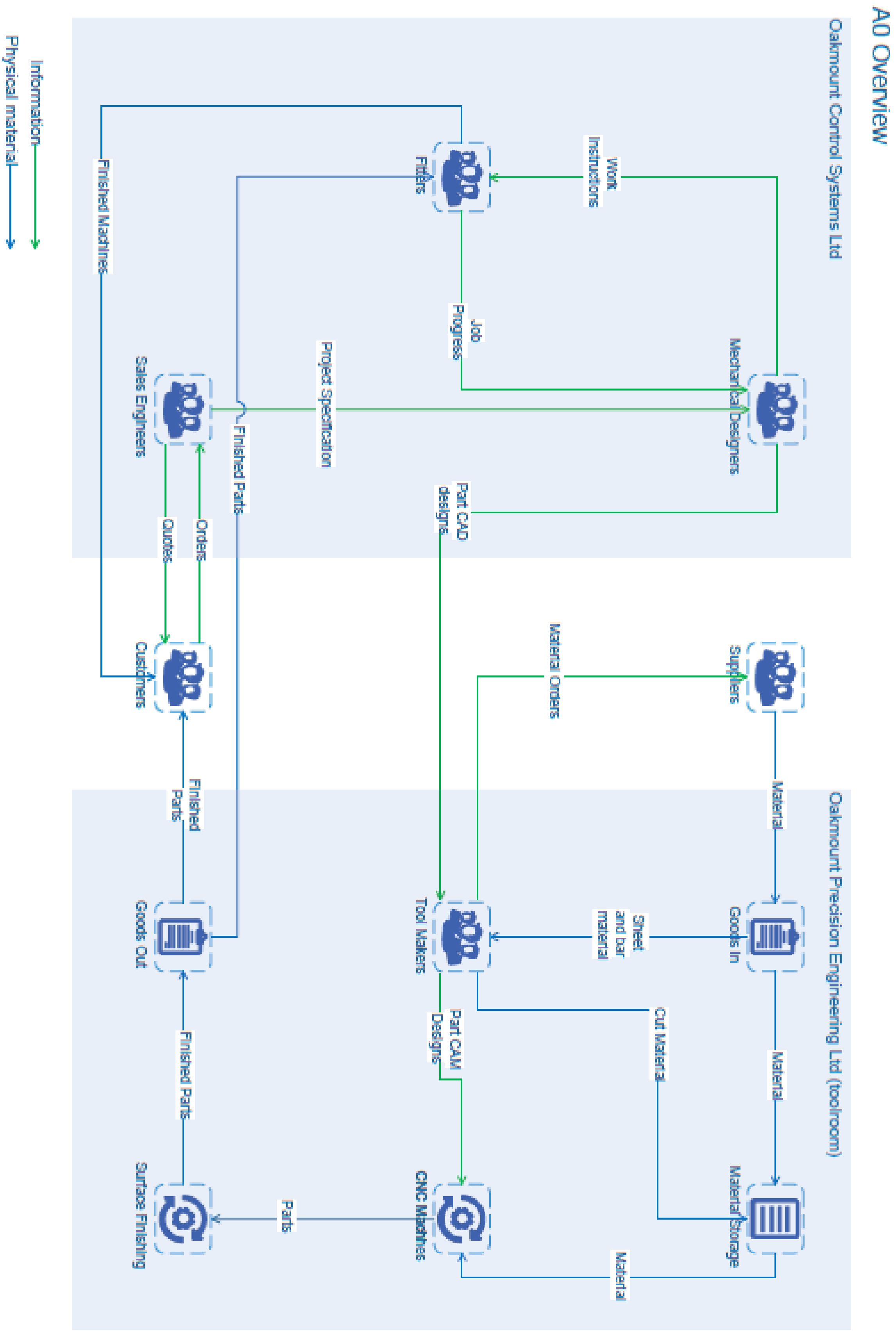


Figure 54: The AS-IS diagram requested by the external provider of factory control software.

Consultancy experiment details

The next tool developed was a robot cycle time calculator to overcome the problem of committing to a cycle time before any equipment has been purchased. Often customers require a cycle time or takt time that they have calculated from the number parts needed per year (takt time) or through recording the time that people take to perform an action (cycle time). Calculating whether a specific robot and ancillary machinery can achieve this is difficult due to the wide range of possible activities and nascent nature of the proposed process.

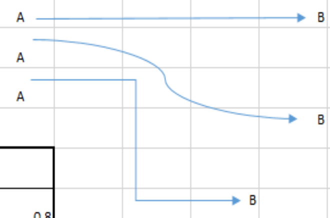
Robot systems were observed during programming and factors affecting the speed were identified. As many different robots are available and each operates at its own speed this has to be included as part of the calculation and modified by various factors (Figure 55). These include the efficiency of the path, defined by obstacles, changing height and linear or joint movements. Linear movements move the end effector in a straight line in relation to its surroundings, whereas joint movements move from point to point on a path that is fastest considering the kinematic chain and speed of each joint. Joint movements are typically quicker than linear ones. The spreadsheet provides sections where these factors can be calculated and then they are entered into the Path Efficiency Factor table, which combines them into an overall factor to modify the robot end effector speed. This is calculated for each movement and entered into the cycle time calculator table along with the speed and distance to calculate time to complete a movement.

Cycle time calculator - Enter data into grey cells	
Motion	
Estimated speed of end effector (m/s) *	1
Distance end effector must travel (m) path 1	1
Path 1 efficiency factor **	0.494
Distance end effector must travel (m) path 2	2
Path 2 efficiency factor	0.494
Distance end effector must travel (m) path 3	
Path 3 efficiency factor	
Distance end effector must travel (m) path 4	
Path 4 efficiency factor (%)	
Motion time (s)	1.482

Path Efficiency Factor - Choose from Dropdowns	
Obstacle Factor	0.65
Linear or Joint move	0.8
Height Change	0.95
Total	0.494
* refer to robot options tab column R	
** Use Path Efficiency Calculator for Path	

Obstacle Factor	
No obstacles	1
Moderate obstacles	0.8
Extreme obstacles	0.65

Obstacle Factor Examples



Linear vs Joint Move	
Linear (end effector moves in straight line - normally less efficient)	0.8
Joint (robot take most efficent path from point to point)	1

Height Change (robot moves in Z)	
Yes	0.95
No	1

Figure 55: Robot cycle time calculator tab of the sales assistance tool showing estimation tables for robot movements.

To produce the factors experiments were conducted with two different robots and data collected on the time in milliseconds for them to perform a set variety of movements (Table 44 in Appendix B). The mean time of each movement type was then calculated and compared to yield a proportion factor. These were inserted into the tool and then used to estimate the cycle time of a proposed system. Other times that had to be estimated were the time to perform manipulation and sensing and any time the robot was waiting for other processes to finish. When the system was completed, the estimate was compared with the actual cycle time and found to be very close. In one test, the spreadsheet calculated a cycle time of 22 seconds and the finished machine after a lot of optimisation achieved 20 seconds per assembly on average. However, the robot used on the system was one of those that performed the data gathering for the tool. Data from more robots would be required to make the tool generalisable to any robot. This data may reveal the necessity for further changes to the tool or separate tools for different classes of robot. This tool can be used at the specification stage to help sales engineers calculate a realistic cycle time that can be specified on the quote. Inversely, if a customer requests a specific cycle time, its possibility of being achieved can be estimated. Through field testing the tool was found to be rapid to apply, useable by managers, has low resource use, is suitable for ETO products and is useable at the early stage of planning. It does not consider costs other than financial (cycle time can be converted into cost per product) although these could be added.

Another consideration for cycle time of a machine with a robot is the sequence of tasks the robot must perform. The robot can only perform a single task or movement at any one time and other processes within the machine will also have their own processing times. Calculating the most efficient sequence for the robot to perform when several stations must be serviced is difficult. This was required for a specific project at the host company and existing methods were unable to perform the required estimation. These involved moving pieces of paper around on a tabletop; large squares for each station and smaller ones for each work piece. Methods like this are suitable for simple machines where the robot completes all operations and then begins a new cycle. However, the robot was required to perform out of sequence loading and unloading operations due to the relatively high pressure testing times and parallel stations. A new tab for the sales assistance spreadsheet was created (Figure 56 and Figure 57). This incorporated a table for entering the required process steps and their times and assigning a coloured key to each. The time for each process was represented as a row of cells, one for each second and shaded a different colour for each process. When these are placed end to end they represent the overall machine sequence and allow analysis of available robot 'downtime' when other machine processes are being completed. These can be used to complete other tasks such as loading components at earlier stages of the process. Each line represents the journey of one product through the production process and depending on the 'free time' of the robot, multiple products can be processed in parallel.

Using the tool was more time consuming than the pieces of paper method but for complex machines the paper method was not able to produce a result. The graphical nature of this tool makes it easy to understand and allows complex calculations to be completed without mathematical formulae simply by counting cells. Cycle time can be considered a financial factor as lower time means more products produced resulting in higher profits so this tool does not address non-financial factors. Being enacted in a spreadsheet and completed by one engineer keeps the resource cost low and the tool was developed specifically for an ETO product. The tool uses estimates of time to perform actions along with known cycle times of other machine processes. This could make it difficult to use at the planning stage if the information was not available.

Step	Description	Time (s)	Task total (s)	
1	Move to pick point	1		
2	Pick filter	2		
3	Move to spinweld	2		
4	Place filter in spinweld	2	6	1
5	Move to next task	3	3	
6	Pick bowl	2		
7	Move to spinweld	2		
8	Place bowl in spinweld	2	6	2
9	Move to next task	3	3	
10	Spin weld	16	16	
11	Pick assembly from spinweld	2		
12	Move to valve assembly machine	2		
13	Place in valve assembly machine	2	6	3
14	Move to next task	3	3	
15	Assemble valves	16	16	
16	Pick from valve assembly machine	2		
17	Move to leak tester	2		
18	Place in leak tester	2	6	4
19	Move to next task	3	3	
20	Leak test (3 stations)	140	50	

Figure 56: Data entry fields for robot sequence calculation tool

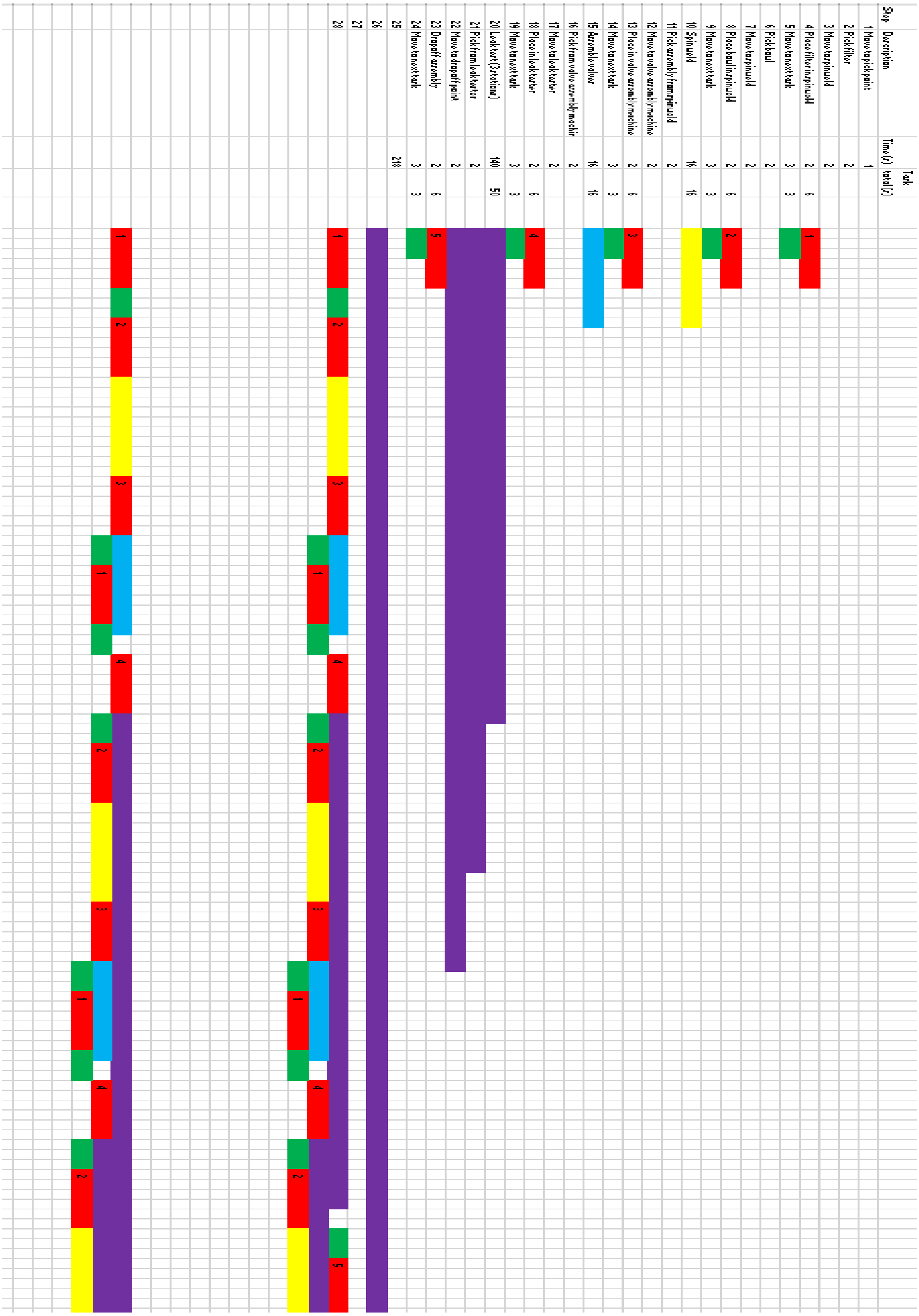


Figure 57: Robot sequence calculation spreadsheet with a list of tasks and times in the top left and the coloured robot sequences for different options below.

Another aspect that is important for automated production machines is safety. Reading and understanding the legislation and performing the calculation is time consuming but was performed by the author for two customer cobot applications. To reduce future effort and produce repeatable results the calculation was incorporated into the sales tool (Figure 58). Testing was limited to one proposed system and only used by the author. To validate the tool it would need to be applied to more systems and used by untrained participants.

Safe cobot speed calculation (ISO 15066:2016)	
Reduced mass of two body system	
μ=(1/mH+1/mR)-1	
mH (hand in kg from table A.3) =	4.4
mR (mass of moving robot in kg - whole robot mass used) =	20.6
μ (kg) =	3.6256
Maximum allowable relative velocity	
Vrel = Pmax*A/sqrt(μ*k)	
Pmax (Maximum allowable pressure in N/cm2 for back of hand from Table A.2) =	380
A (Contact area in cm2) =	0.5
k (Spring constant of hand in N/m from table A.3)	75000
Vrel (m/s) =	0.364362

Safety laser scanner protection zone calculation (ISO 13855:2010)	
S=K*T+C+A	
K (Approach speed of person mm/s (min 1600))	1600
T (Overall response time s (robot 0.5 + scanner 0.06)	0.56
C (1200-0.4*H)	800.4
H (Height of detection plane mm)	999
A (Supplementary necessary distance mm)	100
S (Safety distance mm)	1796.4

Figure 58: Safety calculations in accordance with ISO 15066:2016 for speed of cobot and laser scanner protective area.

When the human to robot contact conditions are not acceptable, the system must be guarded in the same way as an industrial robot. Through consultation with customers, it was found that completely fencing off the system was not a preferred option due to increasing the perceived hazard of the robot among the workforce. Light curtains were also not possible because of the large distance required between the hazard and the device. The reason for this is that the system must stop the robot when the curtain is broken at the specified minimum approach speed of 1600mm/s. The long stopping time of the cobot (~500ms), means the distance must be approximately one metre between hazard and light curtain. The chosen solution for this project was a laser area scanner that can detect intrusions into its protective zone and stop the machinery, which has the benefit of being mounted to the machine and scanning outwards. The calculations for light guard distance or protective zone, while relatively simple must be performed as specified by the regulations. To save the engineers' time and ensure correct application these calculations were also included in the sales assistance tool spreadsheet (Figure 58).

Another tool created to help engineers was a lookup table tab to help select robots in the sales assistance spreadsheet (Figure 59). This comprised a number of columns with various useful specifications and a separate row for each robot model. The table was constructed through an actual need to identify the best robot to use for loading parts into computer numerical control (CNC) machines from a mobile platform. This required consideration of the weight of the robot to ensure it was within the capability of the AGV platform to carry. Another factor was the maximum reach of the robot to ensure it was able to place parts in the desired positions in the CNC machines. This figure was found using a tape measure and Pythagoras' theorem (Figure 60). Finally the weight the robot can lift, termed payload, had to cover the common sizes of material to be handled. These were more difficult to calculate and involved the analysis of three dimensional computer aided design models (3D CAD models). Each component was analysed using the software to find its mass from the shape and material type (*Figure 61*). These were recorded in an excel spreadsheet and then presented as histograms. This was done for two previously designed machines comprising 184 parts and 65 parts respectively. The histogram for overall part weight can be seen in Figure 62 and presents graphically that most (92%) of the parts were under 3kg. This allows the use of a much smaller robot for automated loading and the larger jobs can be loaded by hand or using the forklift truck.

										Speed (deg/s)							TCP Speed (m/s)	
Robot options	Payload (kg)	Reach (mm)	Weight (kg)	Controller weight (k	Controller size (mm)	Power (KVA	Supply (VAC)	ISO-Cube (kW)	Price (£)	J1	J2	J3	J4	J5	J6	Averag	Seller	Very Rough Estimate
UR 5e	5	850	20.6	13.6	475x423x268		100-240VAC			180	180	180	180	180	180	180	1.00	2
Kuka KR30HA	30	2033	665		615x580x540		380-575, 3-phase			140	126	140	260	245	322	206		3
Yaskawa GP35L	35	2538	600	70		4				180	140	178	250	250	360	226		3
Yaskawa MH50 II	50	2061	550	150-250		4				180	178	178	250	250	360	233		3
Kawasaki RS030N	30	2100	555	40		7.5	200-220, 3-phases			180	180	185	260	260	360	238		3
ABB IRB4400	60	1960	1040			7.8	200-600			150	150	150	370	330	381	255		4
ABB IRB2400	20	1550	380				200-600	0.67		150	150	150	360	360	450	270		4
KUKA KR6 R1820	6	1820	235	33	271x483x460	2	200-230VAC			220	210	270	381	311	492	314		4
Kawasaki RS10L	10	1925	230	40						190	205	210	400	360	610	329		5
Kuka KR 12 R1810-2	12	1810	255							200	185	190	430	430	630	344		5
Yaskawa MH12	12	1440	130							220	200	220	410	410	610	345		5
Fanuc M-10iA/12	12	1120	130				380-575, 3-phase	1		230	225	230	430	430	630	363		5
ABB IRB 1200	5	900	54	28.5	320x449x442	4.5	200-600	0.39		288	240	300	400	405	600	372		5
Fanuc M020iB/35S	35	1445	205				380-575, 3 phase	1		205	205	260	415	415	880	397		5
Fanuc LR Mate 200 iD/7L	7	911	27	55	470x320x400	1.2	200-230VAC	0.5		370	310	410	550	545	1000	531		7
Yaskawa MPK2F-5	5	900	72	20	470x200x420	1.5	230VAC			320	330	330	NA	380	2000	672		9
Fanuc CR-35iA	35	1800	990				380-575, 3-phase	1		750	750	750	750	750	750	750		10
Staubli TX2-60L	5	920	52.5	38	270x445x365	2			22500-23850	435	385	500	995	1065	1445	804	11.00	11

Figure 59: Robot comparison table with the robots in rows and each column showing an important specification.

CNC Machine Robot Reach Calc	DuGard 1350E	DuGard 1000E	DuGard 760E
Bed X (mm)	1500	1200	910
Bed Y (mm)	600	480	380
Robot centre distance from edge of bed (assume central in X) (mm)	300	300	300
Reach required for robot to each farthest corner of DuGard (mm)	1172	984	818

Figure 60: Screenshot of tool for calculation of robot reach required.

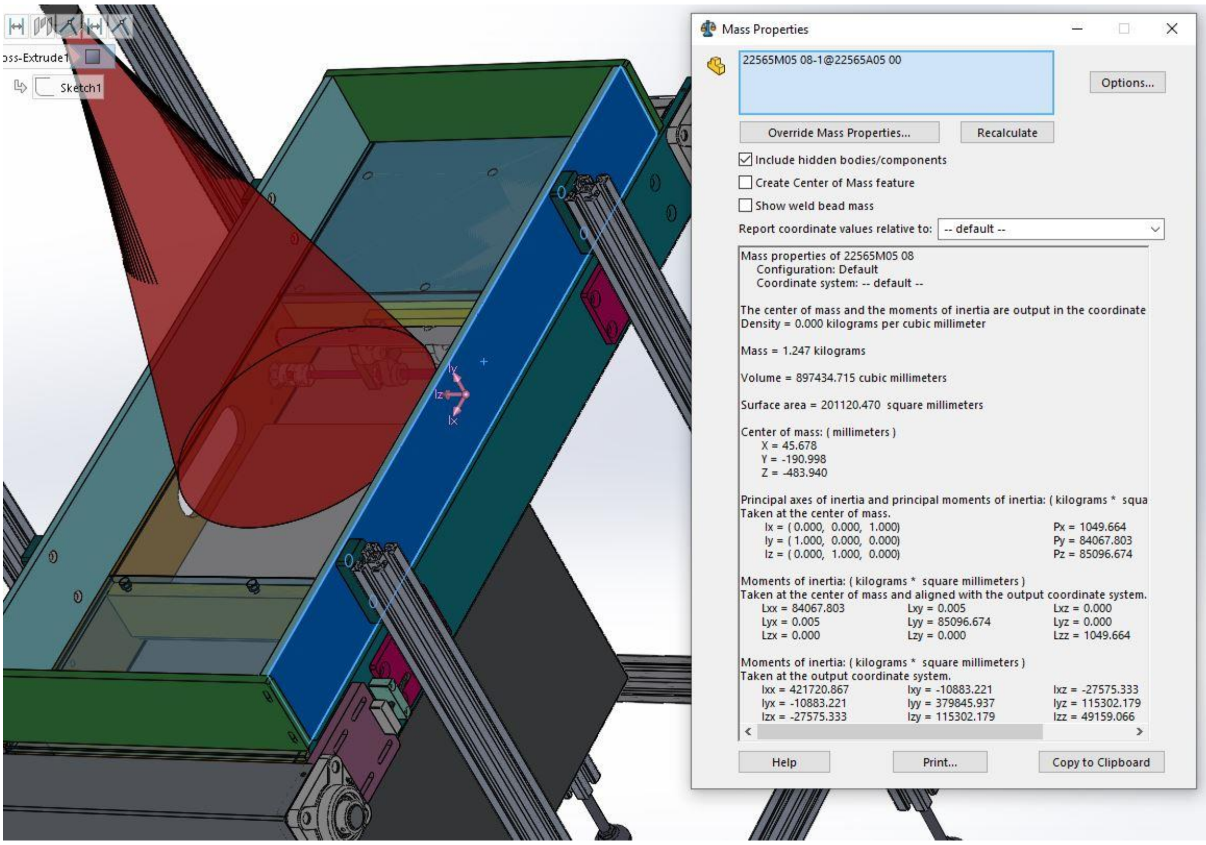


Figure 61: Analysing the properties of CAD components.

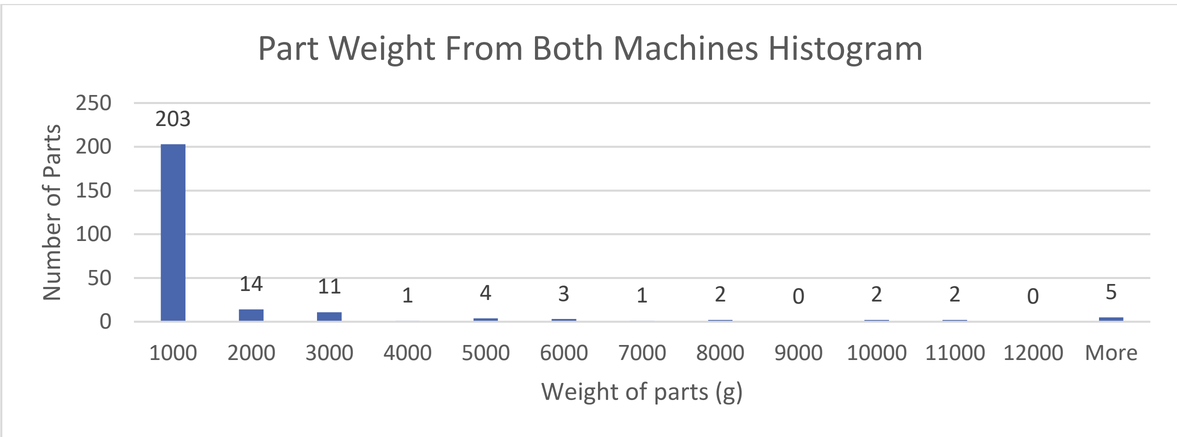


Figure 62: Histogram of the machined part weight's of two produced automated machines.

Another important factor when selecting a robot is its speed as this directly affects the cycle time of the process. Unfortunately, this is not a simple number due to being a kinematic chain comprising the speed of each of the joints and the lengths between these joints. Due to this, many manufacturers do not publish overall speed in their literature but rather the speed of each joint individually in degrees per second. This makes it difficult to compare robots based on their speed. To overcome this the average of these joint speeds for each robot was calculated. This does not take into account the lengths between joints or the comparative importance of joint speed between different joints. For example, the joint closest to the end effector (J6) must often make the largest movement and so limits the speed of the whole robot. To assist direct comparison a rough estimate of tool centre point (TCP) speed was calculated. This was done by calculating a constant using the average joint speed and the published figures for TCP speed of two of the robots and then using the constant to calculate numbers for the rest of the robots. This is an extremely crude way of ranking the speeds and even between these two robots with published speeds; there was a large difference in average joint speed to published TCP speed ratio. These were 72.4 for the Staubli TX2-60L and 180 for the UR5e. Through measurements taken using the actual UR5e the TCP speed was found to be closer to 2m/s giving a ratio of 80. When averaged with the ratio of the Staubli this resulted in a constant of 76.2, which was used for all robots. The estimation of overall robot speed from its individual joint speeds could be useful in comparing robots directly. However, in practice other factors influence the decision of which robot to use. These include price, lead-time, customer preference and availability.