Developing Efficient Workflows for Contemporary Design Processes and Robotics

By Cameron Smith

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Abstract

This Master's thesis forms a section of a team based research project with the aim to understand how contemporary tools can inform a contemporary design workflow. This workflow is primarily focused on utilizing a robotic arm to incrementally form sheet aluminium into architectural components. Specifically, my role within this team is from the Project Management point of view trying to understand how Project Management can improve team focused contemporary design. The goal of the thesis is to establish a workflow outlining an efficient process for designing and fabricating prototype architectural systems.

Research Questions:

> ***Team****: How can contemporary tools inform a contemporary digital workflow?*
>
> ***Individual****: How can Project Management improve the performance and efficiency of team focused contemporary design workflows?*

The aims of the research are to first establish an understanding of the digital fabrication workflow and establish what management tools best fit within the workflow. This aligns with the team goal to create and establish how digital fabrication and robotics could be applied to New Zealand construction practice. The goal is not to suggest a replacement for current methods, but to understand and integrate a methodology using a parametric design process and, to aid the introduction of complexity in design not currently available through traditional construction and joinery methods. Understanding the function Project Management has for workflow management and development is a primary research goal which can be broken down into parts.

- How can activities be efficiently designed?
- What procedures need to be implemented?
- What are the best process management techniques ?

The knowledge gained through an iterative work study shows that project managers have a unique perspective within the development of digital fabrication workflows. A project manager integrated into this process is able to influence and define the key performance indicators of projects undertaken within this contemporary environment. The method used to establish and develop a workflow for digital fabrication processes, is a work study. This involves developing a workflow based on similar cases and then redevelop it based on performance indicators from literature. Identifying key areas of failure is a part of this process and is a common method within industry for improving organisation efficiency and productivity. A limiting factor of this research is the fact the team was learning the process overtime. Therefore, people are subject to unequal levels of understanding of what needs to be considered as part of workflow development gaining new perspective with hindsight. This is not, and cannot be accounted for, however is noted as part of lessons learnt during the reflection process of the work-study.

Glossary

- Digital fabrication – The idea of transforming digital data into tangible, physical products.
- Parametrics – Design relating to or expressed in terms of a parameter or parameters
- Fabrication Process – A process of constructing, or combining parts into a product.
- Knowledge Management – Providing good access to information in an organization
- Process Management – The management of information flow in an organization
- Project Life Cycle – Series of activities required to complete a project
- Robot – A fabrication arm designed to be controlled by a computer.
- Workflow – Progression of steps (tasks, events, interactions) that comprise a work process. *The organisation of documents, information and tasks to be passed from one action to another*.

Key Terms

- Product – The result, or output from a process or method.
- Input – Effort or requirement preceding a task
- Output – The result or product of a task
- Task – A step or role, as part of a larger process

To my family, friends, and supervisors, thank you for your continued support. Your guidance has kept me going these past twelve months.

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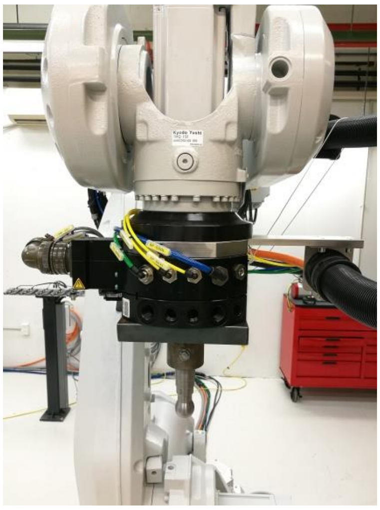
1.0 Introduction

Think Machine is a team comprised of four master's thesis students, three completing architectural studies and one completing a masters of Project Management. The team has the research goal to establish how contemporary tools inform a contemporary digital workflow.

Think Machine utilizes a robotic arm, much like those which fabricate cars, to produce architectural panels from formed aluminum sheets. The robot is programed through parametric software (Grasshopper / Rhino, Catia,). Within the software, fabrication movements can be simulated before moving into physical space thus enabling users to check how the robot will respond to commands before entering them. The robot operates with a 6-axis arm, able to move in far more directions than tools like 3D printers and C&C machines.

Fabrication with the robot begins with a computer program which will send points in space to the robot. The robot is able to trace the points extremely accurately essentially enabling any shape to be programmed and drawn in space. Think Machine are the first students within Victoria University of Wellington to have access to the robot and therefore have both a large advantage and disadvantage. The scope of possibilities for design is limitless, however tools for use with the robot will need to be designed and created by the team. For this research, Think Machine has limited the scope to focus on incrementally formed aluminum sheets. Incremental forming is a process where the robot will repeatedly draw a shape on the sheet, pushing into the material 1,2 or 3mm at a time slowly pushing out the desired form. The sheets are locked in place within a series of Jigs hand crafted for this research by Think Machine.



The role of project management and its incorporation into developing this Digital Fabrication workflow is the focus of this research thesis. The aim is to first establish an understanding of what processes exist in fabrication and construction with similarities to Digital Fabrication. After establishing the key precedent processes, tools, and techniques can be implemented which can provide vital coordination of the design process. Meanwhile, to analyze the performance of the final workflow, an in depth literature review will investigate performance assessment and management processes for developing workflows.

Projects completed by Think Machine include a pavilion design (named Tatu, Portuguese for armadillo), a smaller component of a shading system, and finally a full scale developed design utilizing similar design language as the previous shading system. Early in the development and exploration phases of the research, a proposed project was to adapt and design shading systems for a small seaside bach. However, the design process moved away and focused on robotic control within the pavilion shading system context.

Efficiency is the key performance indicator of workflow performance along with consideration to productivity and quality of processes. The integration of various management techniques and tools has been used to assess the development and performance of Digital Fabrication. Assessment is made against how well integrated ideas perform with regard to Efficiency, Productivity and Quality. Moreover, as this is not only a development process, but a learning process, the effect of people becoming more familiar with tools as research progressed is outside the scope of research.

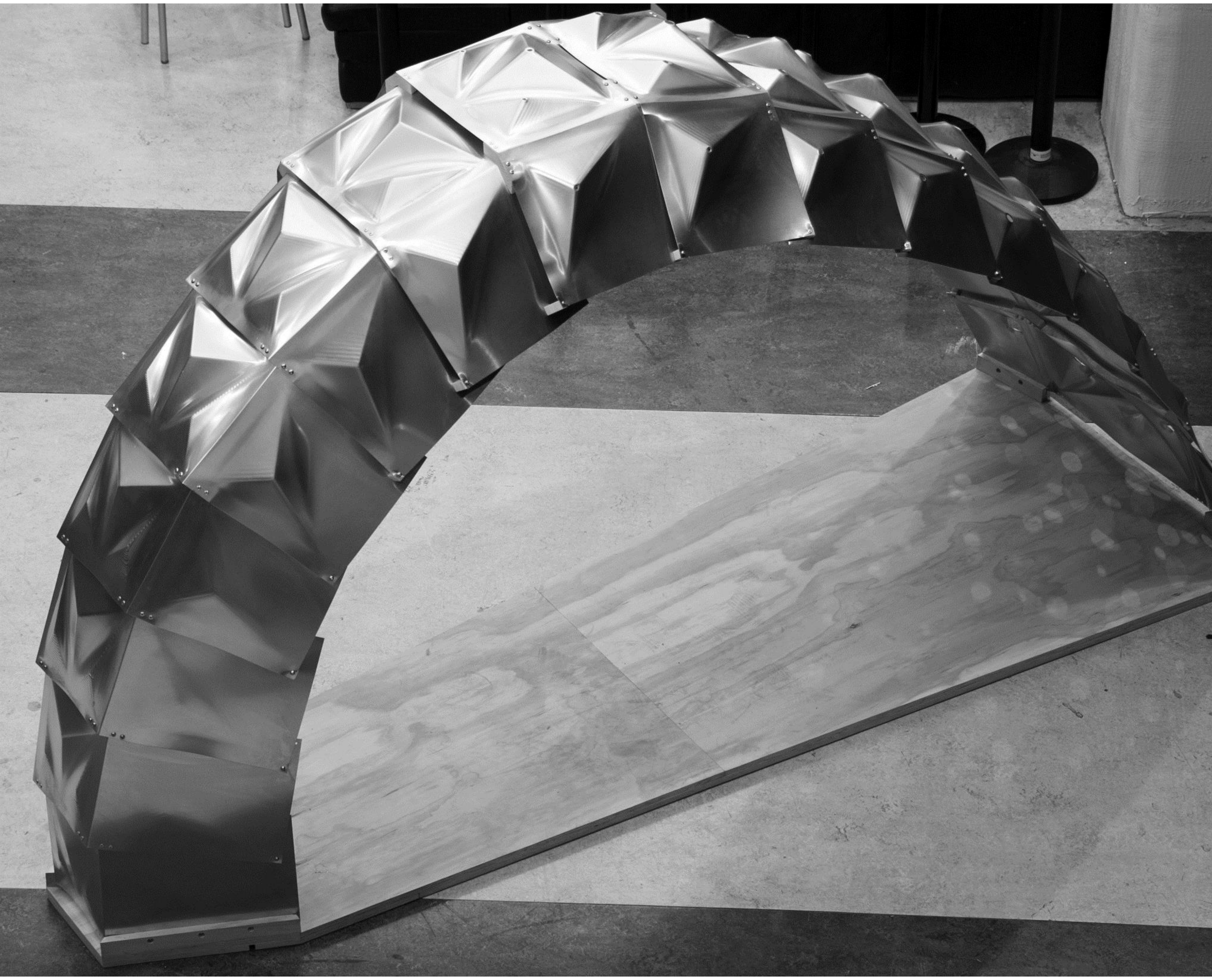
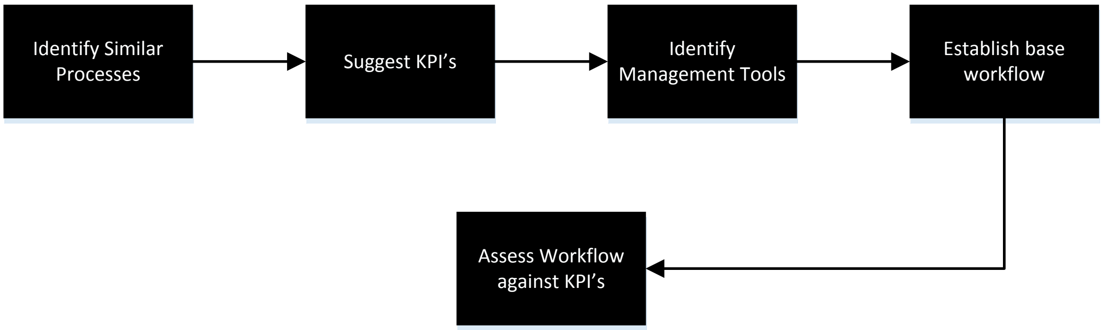


Image: Tatu, the first milestone project completed

1.1 Research Design



1.1.1 Identify Similar Processes

The first stage in the research is to identify what existing comparable tools and processes exist in relation to digital fabrication. This involves defining digital fabrication and how the process can be managed. Investigation into the core ideas of fabrication and contemporary design processes are an essential step in this research. Methods such as building information modelling are valuable precedence for establishing a base workflow for digital fabrication and highlight useful management philosophies to establish early in the team environment.

1.1.2 Performance Indicators for Workflows

After identifying precedence examples of 'similar' processes, the second stage of research is to suggest a range of key performance indicators (KPI) for the workflow. Key performance indicators provides a means to assess the effectiveness of techniques employed in the research.

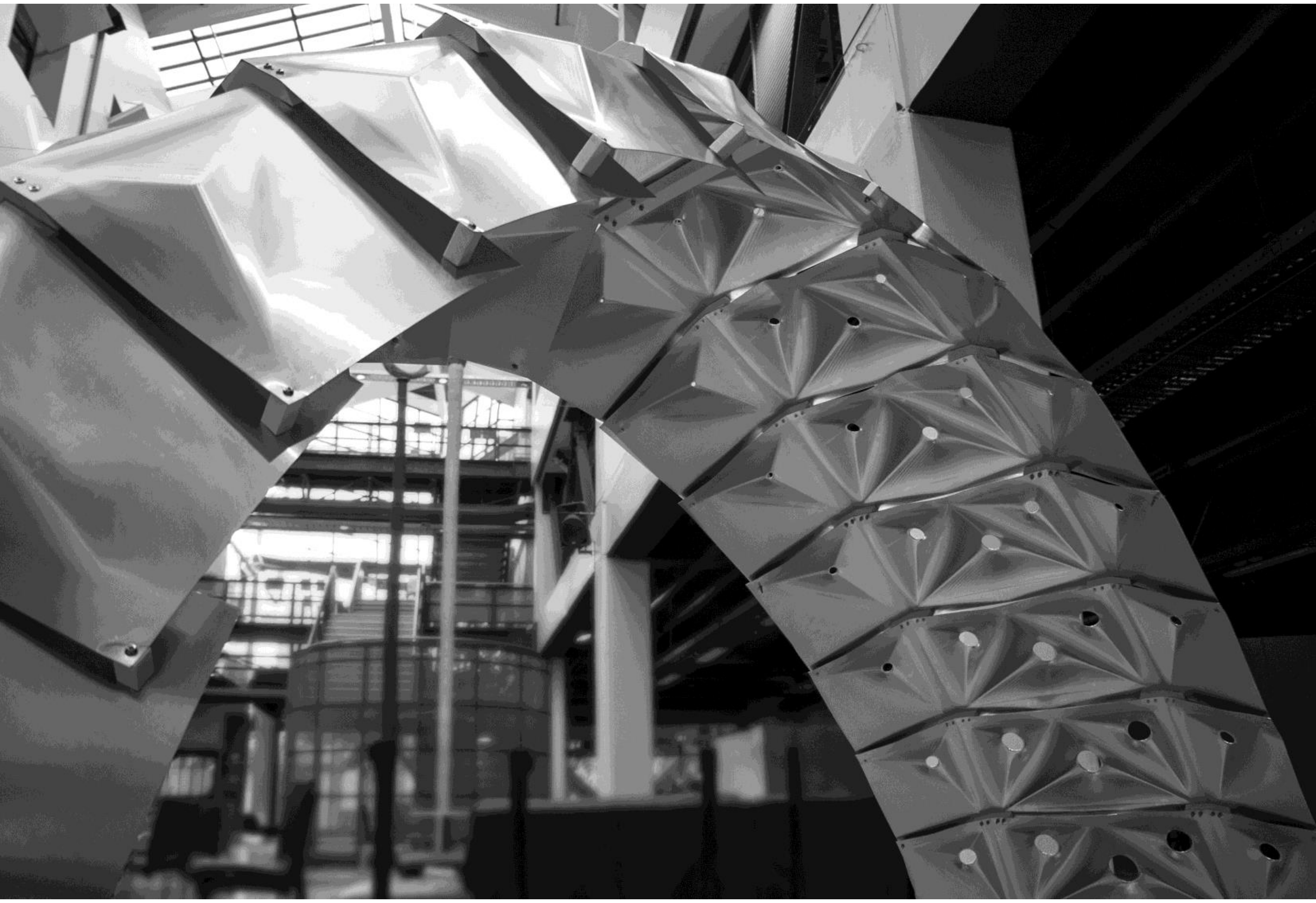
The main knowledge gap to be identified is how the performance of the process should be assessed. The similarities between existing processes and digital fabrication suggests a start point to testing and developing management tools. A crucial part of this discussion is the limitations in which performance assessment can be applied must be revisited in discussion of the results at the end of this thesis.

1.1.3 Techniques to manage workflows

Once the performance indicators have been identified the intention is to focus on techniques that can be appropriately used and assess the effectiveness of them in the situation. Looking heavily at existing management and organisational methods the research will adopt ideas based on solving issues identified under reflection. The focus is not on replicating these methods as is never the case in real world management, but instead to draw out the core function of techniques and apply them in contemporary ways. Identifying strengths and weaknesses within management techniques and applying them will be essential in creating effective workflows. The goal at this stage of the research is to understand how management techniques and the workflow in general can be assessed against the key performance indicators.

1.1.4 Base Workflow

Start for Think Machine (initial ideas) The practical application of the thesis first involves creating a base workflow for Think Machine and set up initial management tools to aid in the progression of the team goals. This will be a workflow based primarily on tools and points identified as important by literature and precedence methodologies. Much like design, assessment and critical reflection of this first workflow is fundamental to the ability to develop further. The aim for this tool is to be useful to the team and demonstrate good performance of the key performance indicators (KPI's). Given the scope of a masters research thesis at this early stage, the workflow tool cannot be considered a compete tool. The goal for the remainder of research is to assess, reflect and develop suggested tools further. The final result will be a prototype methodology for integrating a specific contemporary tool into a design process. KPI's will be assessed at all stages of workflow development and significant changes should be expected from the initial suggested workflow as the team develops skills and knowledge on the topic.



2.0 Introduction to Literature

This literature review investigates digital fabrication and management principles to highlight the key points in defining performance for a robotic design fabrication workflow. This involves understanding what a fabrication process is and what synergy there is between the traditional ideas and digital fabrication. In understanding the similarities and differences between Fabrication and Digital Fabrication, management ideas can be applied which are best suited to resolve and organise the final design process. Efficiency is the core component of project management, Process Management, and Knowledge Management are both investigated as part of this literature review to understand what ideas can be applied during a digital fabrication project life cycle.

2.1 The Fabrication Process & Workflows

There is a large variety of types of work which create a great many 'things' today. For example, baking bread, making a bed, designing a house, building a skyscraper. All of these 'things' have steps and processes integrated together to create the final product. This complex amalgamation of steps such as adding yeast to flour before baking bread, or installing steel beams before pouring concrete in a skyscraper can be organized by a workflow. For this thesis, the work output or 'thing' will be called a product, with what guides the processes the 'workflow'.

2.1.1 The Fabrication Process

Fabrication is a process of constructing, or combining parts into a product. Essentially this is the construction of products that are made from either pre-assembled or designed components rather than starting from scratch. Take residential construction for example, rather than building the sub-construction of a wall piece by piece, a fabricated wall would come to site as a single framed unit. A fabricated component has no limit to the complexity and serves the function to significantly reduce the on-site construction workload. Fabrication is designed to help prevent or at least minimise the variation common in a construction or manufacturing process (Kumar & Sivanandadevi, 2014). Fabrication is not a process native to the construction industry and is not widely integrated into New Zealand construction. Prefabrication and the development of Building Information Modelling (BIM) in New Zealand however, has begun to strengthen the idea of fabrications place within the construction industry.

2.1.2 Building Information Modelling and Construction Sector performance

Productivity development within the construction industry internationally for the last 40 years has been sluggish by comparison to other industries (Lindblad, 2013). Hannes Lindblad argues that this is a combination of the "collaborative needs" of construction, and the "fragmented nature" of the construction industry (Lindblad, 2013, p. 1). BIM as a construction process has begun its slow integration into the construction industry over the last two decades, consistently insisting that it is the greatest technological advance in efficiencies (Hardin, 2009, p. 35). In essence, BIM provides a foot hold for the future development of parallel fabrication processes as it provides the platform to expand process development away from the normal design and construction. A significant issue is a misconception that BIM is not feasible on smaller scale projects (Eynon, 2014, p. iii). John Eynon argues in 'BIM in Small Practices' that the BIM methodology can be applied to small projects (Klaschka, 2014). BIM software was developed and continues to develop as a response from design professionals who have the need for a singular point of reference in a project (Hardin, 2009, p. 35). Moreover, the focus of BIM development is not focused to technological and computerized development. A good BIM process involves a significant mind shift for the users to work in a more collaborative nature outside of the software. This central source information allows a design or construction team to share, add to, and alter to, then be shared and responsibly distributed to a wider team (Hardin, 2009). These four points in a BIM process can be accredited to the benefits of the process. According to John Eynon, the benefits of this process have five distinct impacts (Eynon, 2014, p. iii):

- Improved collaboration.
- Better design and coordination.
- Increased efficiencies and productivity.
- Better coordination and communication with contractors.
- Faster, more accurate, and more effective ‘optioneering’ of alternate solutions.

It is argued that these broad impacts have positive connotations for both large and small scale construction projects (Hardin, 2009; Jernigan, 2008; Klaschka, 2014). Despite this common belief, most case development is focused to larger projects. According to BRANZ, 91% of companies in the NZ construction sector are defined as a small firm (Curtis, 2014). Recalling Lindblad’s view on the international construction industry’s poor productivity, small firms representing the majority of the market generally focus on smaller scale builds. Integrated into contemporary design and construction methodologies the fabrication has been shown to have significant impacts in term of productivity and efficiency (Lindblad, 2013; Moghadam, Alwisy, & Al-Hussein, 2012). Contemporary fabrication processes offer the larger market share the platform required to increase their process efficiency resolving the underlying performance issues of the construction sector.

2.1.3 Defining features of workflows

Definition is important when designing new processes, and before deciding to implement a new process is it very important to first establish whether it will work properly. This is defining the purpose, and reference to assess the process on (Van Der Aalst & Van Hee, 2004). To give a definition of a workflow, the purpose must first be discussed. According to Vanderfeesten and Reijers, the purpose of integrating workflows into a business environment is to streamline and improve business performance (Vanderfeesten & Reijers, 2013). Moreover, the purpose is to improve the service, and quality of products. This can be interpreted in many ways namely that the focus of any workflow is in advancing more than one key area; Quality, Time, Cost, Perception and most significantly Efficiency. Amongst these points that fall within the supposed focus, Reynolds suggests that a workflow allows the tracking of processes (Reynolds, 2007). Essentially, a workflow is supposed to help improve overall performance of any process by being a simple, efficient and traceable rule set.

Going back to the 1950’s, the interpretation of work flow was simple and suggests the priority use is to help identify and solve issues;

> “work flow diagrams are effective in solving various solutions”(Herrman, 1950).”

A more recent interpretation of what a workflow is and what purpose it serves is varies dependant on both who has written it, and who is reading it. The workflow management coalition, a global organization of adopters, developers and practitioners engaged in Workflow development and management label a workflow as;

> The automation of a business process in whole or part during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules (WFMC, 1996).

The business dictionary, although not directly involved with the management or understanding of workflow implementation offer a widely adopted definition;

> "Progression of steps (tasks, events, interactions) that comprise a work process, involve two or more persons, and create or add value to the organization's activities. In a sequential workflow, each step is dependent on occurrence of the previous step; in a parallel workflow, two or more steps can occur concurrently" (Business Dictionary, 2016).

There are, in fact, countless definitions for workflow moving through history and they generally seem to increase in complexity over time. Reading these definitions, it is clear that as time has progressed, and people have created more workflows for specific work cases, a definition is drafted to reflect how it is used. This is the core of what a workflow is; where it is only useful for one function, and only understandable by people familiar with the context it is used in.

As stated, there are many definitions for what exactly a workflow can be, often focusing in on the business management and back end requirements to manage a set of processes. They typically separate work activities into well-defined tasks, roles, rules and procedures which regulate most work (Georgakopoulos, Hornick, & Sheth, 1995). Definitions such as this are repeated and refined hundreds of times over with a general understanding that a workflow is the process and procedure in which tasks are completed. There are issues with adopting these definitions for use in developing a workflow, namely that fact many definitions are written based of past working methods and therefore do not take in into consideration generational and philosophical changes in management (Van Der Aalst & Van Hee, 2004).

The fact remains that detailed definitions of this simple concept are unnecessary as it defeats the purpose, to give traceable and efficient methods to any process. The key success factors relate simply to establishing good management processes, strong communication channels and most importantly user interaction. Over complication of this leads only to confuse what the workflow should focus on. Therefore for the purpose of this thesis, a workflow will be defined by the management of a process detailing a specific pathway required to achieve the desired output. More specifically, *the organisation of documents, information and tasks to be passed from one action to another*. Ultimately, defining a workflow comes full circle and is not helpful in creating one. Through providing a definition, some aspect of what should be focused on is either lost or forgotten in translating it. What is actually most important is very simple; a workflow relates to how an organisation works.

2.1.4 Process Improvement

Workflows affect processes, and processes have many steps which allow for a degree of inefficiency, no matter how well organised it is in the first instance. The basic understanding about why a workflow is used can be simplified into improvements to the process, and benefits to a group. Moreover, many studies indicate that successful implementation of workflows into organisations improve measurable performance.

Claims listed to improve processes

- Improve communication
- Increased Productivity
- Enforce consistent procedures
- Adherence to procedures
- Faster time response
- Higher quality of outputs

Claims listed to benefit organisations

- Workflow may be a solution to current problems
- Workflow may be a means to improve procedures
- Design unique solutions
- Measure and monitor performance objectively
- Morale

These benefits all relate to the management of processes.

Collected from among others (Brahe & Schmidt, 2007; Choenni, Bakker, & Baets, 2003; Georgakopoulos et al., 1995; Han, 2009; Reynolds, 2007; Vanderfeesten & Reijers, 2013; WFMC, 1996).

According to Georgakopoulos, Hornick & Sheth, we can categorize processes in an organisation into material processes, information processes, and processes:

- **Material Process:** The scope of a material process is to assemble physical components and deliver physical products. That is, material processes relate human tasks that are rooted in the physical world. Such tasks include; moving, storing, transforming, measuring and assembling physical objects (Georgakopoulos et al., 1995).
- **Information Process:** Relate to automated tasks (such as tasks performed by programs) and partially automated tasks (tasks performed by humans interacting with computers) that create, process, manage, and provide information. Typically, an information process is rooted in an organizations structure and/or the existing environment of information systems. Database, transaction processing, and distributed systems technologies provide the basic infrastructure for supporting information processes (Georgakopoulos et al., 1995).
- **Business Processes:** are market-centred descriptions of an organizations activities, implemented as information processes and/or material processes. A business process is engineered to fulfil a business contract or satisfy a specific customer need. This the notion of a business process is conceptually at a higher level than the notion of information or material process (Georgakopoulos et al., 1995).

These definitions form the base for process management. Georgakopoulos, Hornick & Sheth, go on to define that an organisation can reengineer their internal processes after defining processes in this way. It follows what is described by Van Der Aalst & Van Hee, as the "First organise, then computerise ideology" This approach does not examine the opportunities offered by information systems implying that processes were developed with the assumption business processes are managed by people (Van Der Aalst & Van Hee, 2004). Workflow is a concept closely related to reengineering and automating business and information processes in an organisation. Moreover, it is a value adding process. Value-adding processes have become more and more the principle of organising the business, rather than a functional hierarchy perspective (Aguilar-Savén, 2004). The appropriate implementation of workflows and workflow management can lead to better productivity as well as efficiency. Workflow management supports the reengineering of business and information processes. This involves (Georgakopoulos et al., 1995):

1. Defining existing workflows. For example, describing the aspects of a process that are necessary to complete the tasks. This may include a description of the required skills or tools.
2. Investigating the inefficiencies in each process and provide fast alternative workflow methods to improve efficiency.

Workflows and the fabrication process enable a significant efficiency gains when defining the order in which tasks need to be executed, who is involved, and defining the rules for how the process is followed. The performance impact of successful implementation however, is not clearly identified other than there is an apparent impact (Vanderfeesten & Reijers, 2013). This is not surprising considering the process required to implement a workflow consists of analysing the process in great detail thus exposing and solving issues.

2.2 Performance Indicators for Workflow Management

Table 1: Performance Impact of Workflow Use and Management

Study	KPI	Impact	Outcome	# Cases Examined	Measurement Method
(Choenni et al., 2003)	Time, Quality, flexibility, Reliability	Mixed	Quantitative	2	Questionnaire
(Brahe & Schmidt, 2007)	Productivity	Positive	Quantitative	1	Quantitative analysis of individual productivity in organisation. (number of cases per day, speed of work being executed)
(Han, 2009)	Desired output (efficiency)	Positive	Qualitative / Quantitative	---	---
(Arashpour, M. 2015)	Time, Rework,	Positive	Quantitative	---	---
(Georgakopoulos et al., 1995)	Efficiency, Quality, Cost,	---	Qualitative	---	---
(Reynolds, 2007)	Productivity, Efficiency, Quality	Positive / Strength weakness identified	Qualitative	---	---
(Aguilar-Savén, 2004)	Efficiency Quality	Positive	Qualitative		
(Hajo A. Reijers & van der Aalst, 2005)	Lead Time, Service time (Quality), Efficiency	Positive	Quantitative	16	Simulation
(Küng & Hagen, 2007)	Cycle time, Productivity	Positive	Quantitative	4	Measurement before and after implementation.

A review on available literature shows the common denominators for key performance indicators (KPI's) to be time, Quality of products, Efficiency of the processes, and the perceived cost reduction compared to pre-implementation. There is a clear opinion that after the implementation of good workflow management, there is a positive change in performance. It would seem that the measure of success varied greatly depending on KPI's and that the individual organisations KPI's are varied. The key point in this information is that KPI's used to measure success of the workflow's integration are related to what the organisation aspirations are(Vanderfeesten & Reijers, 2013). This suggests that ultimately the selection of measurement criteria must have a direct correlation to what the process is creating. For example, of the KPI's identified, Service time, and cycle time are less relevant to construction process however, grouped into Time, Quality, Efficiency and Cost, they become relevant. Moreover, within the realms of this thesis and the academic situation that it is conducted under, cost, reliability and rework have a lower degree of importance when considering the goals of establishing an efficient workflow.

Workflow performance must be evaluated for determining the successfulness of workflow execution (Han, 2009). The primary KPI's that can be established from literature for the performance of workflow integration are Quality, Efficiency and Productivity. This does not separate them as separate from other KPI's such as cost and time, however sets in stone that these are most important for creating the most effective workflows. The reoccurrence of quality of the products and understanding efficiency across literature highlights the importance these two KPI's have in the creation of workflow processes (Vanderfeesten & Reijers, 2013). The studies on organisational impact tend to focus on many additional impacts such as culture change, working environment quality and job satisfaction. These come from a theoretical social science perspective and rarely actually investigate the real users, and real implementation (Vanderfeesten & Reijers, 2013). These studies have indicated positive impacts although indicate a risk of actually making jobs more boring and having negative impacts in productivity as a result. Data is not available on this with real world measurements which is expected as a business will not likely publish data suggesting after their own investment, they have reduced the productivity of their own business (Choenni et al., 2003; Piana, 2001). In reality, the critical KPI's for workflow system implementation identified form literature are comparable to both good fabrication, and building information modelling: eg. Appropriate management techniques, good communication methods and user engagement.

2.3 Productivity and Efficiency

2.3.1 Defining Efficiency

Generally when discussing the efficiency of a product, we are judging its success in terms of being able to have produced the maximum quantity from a set limit of resources. However, this is not the most accurate way to describe efficiency, nor does it accurately relate to efficient workflow management. Throughout management science literature, productivity and efficiency measurements generally focus on smaller aspects of a workflow rather than observing the performance of the larger picture (Vanderfeesten & Reijers, 2013). There appears to be two major schools of thought on efficiency, Technical efficiency and Labour productivity. Traditionally, labour productivity was considered as an average measure of efficiency (Farrell, 1957). Technical Efficiency on the other hand takes into consideration a wider set of factors when determining how efficient a process is. These factors include; the amount of material used, the amount of energy expended, the capital investment in the process. According to Farrell, the previous (labour productivity) understanding of efficiency was not appropriate to be used with regard to technical efficiency as this only looks at labour ignoring other factors such as materials, energy, and capital. Technical efficiency measurement involves comparing a decision making unit's plan to a production plan and has numerous methods to calculate. Nimish Sheth (1999) details the methods including the index numbers approach, the econometric approach and a mathematical programming approach. This thesis literature review however, does not focus on the mathematical methodologies required for detailed measurement of efficiency but only to establish a clear definition for how to best approach the topic of efficiency when developing workflows.

2.3.2 Defining Productivity

At the core, efficiency is the acknowledgement of all inputs with an effect on the output of a process. This can be seen within some methods for analysing efficiency, and is commonly simplified to the notion of inputs vs outputs. For example; looking at fabrication processes, the common measure of efficient productivity has been labour productivity (output per man hours). Another good example of this is utilized in a wider context, the rate of return on capital investment (ROI). These methods are used to analyse the performance of a small component within a wider production process. With this said, the application is not restricted to investigating the small details and is fundamental when assessing the overall efficiency of a large process. The same methods above apply, for example; the individual performance of a task has been evaluated identifying a level of performance, this information is able to be collected across a series of processes and provide understanding to the overall performance of a workflow. In the late 90's, Alan Stainer suggests such measurement ratios face a fundamental flaw. The presence of external factors may affect the ability to provide accurate calculation thus have no actual relationship to efficient resource use (Stainer, 1997). This is in line with Farrell's distinction between different earlier understandings of efficiency in that there are significant additional impacts which prevent simple assessment of efficiency in terms of inputs and outputs. Therefore, the measurement of efficiency cannot be restricted to ratios of input and output within the realms of practice.

"Efficiency is the goal of good workflow management within organisations" (H.A. Reijers, Vanderfeesten, & van der Aalst, 2016; Vanderfeesten, 2004), this is a simple fact that underpins the notion to management. Efficiency is a measure of performance in a workflow and for this thesis, the crucial method of discussion about efficiency of a workflow comes down to quality of outputs.

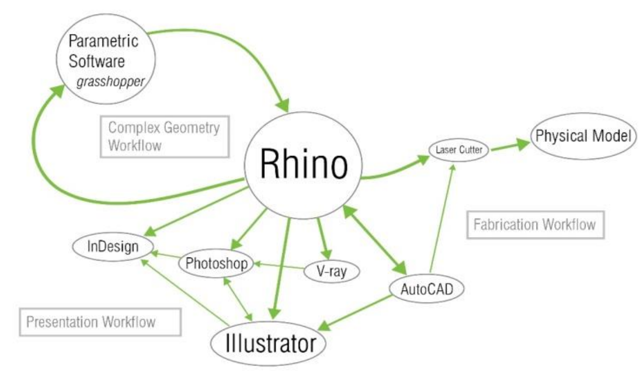
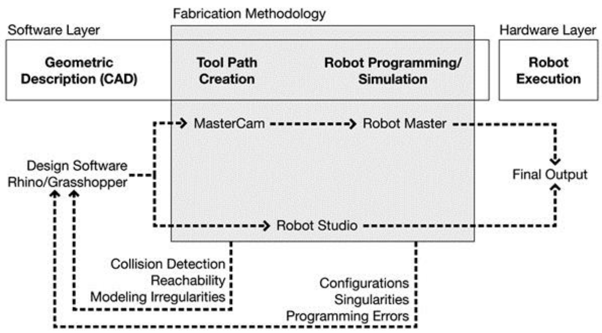
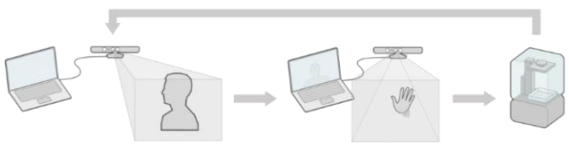
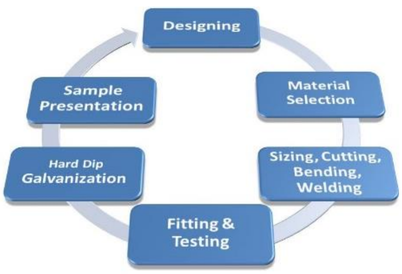
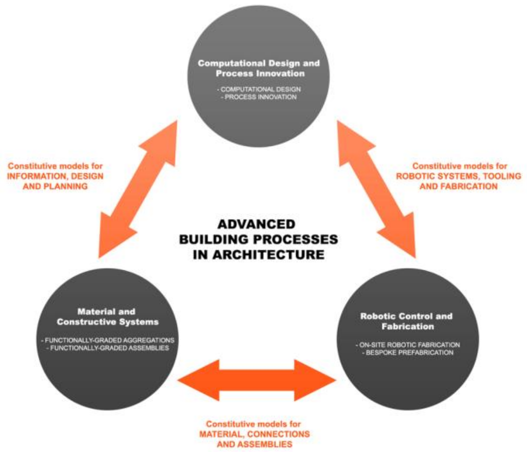
2.4 Digital Fabrication

Digital fabrication in essence, the idea of transforming digital data into tangible, physical products. At a basic level, the process differs very little from the traditional fabrication process. It is shares the goal of constructing, or combining parts into a product. The more complex level however has some fundamental differences from a traditional process for example, Digital Fabrication sets out to facilitate rapid prototyping such as 3D printed components to then be fabricated into a product. Digital Fabrication, is a type of manufacturing process where the machine (tool) being used is controlled by a computer (Opendesk, 2017). Common tooling methods often associated with Digital Fabrication are CNC Machining, 3D printing and Laser Cutting. There are a wide range of additional processes which can be classified also as Digital Fabrication, the important distinction that binds them is that the tool can be programmed to fabricate consistent products from digital designs (Opendesk, 2017). This distinction does not however restrict the tool to replicate a singular output such can be seen in the fabrication of cars and many more. Instead, the quality of the output must be predictably controlled to some degree meaning that you can enter a computer command and have an expected output.

2.4.1 Morality of Digital Fabrication

Digital fabrication is seen in various lights internationally and has become a point of wide debate, especially when considering the replacement of manual labour with robotic intervention. Moreover, there is a real danger of automation leading to "monotonous and boring work" (Vanderfeesten, 2004). In reality, the notion of robots replacing entire workforces is nonsense, however, it does ask a significant question related to the effects morality of robotic construction which is linked directly to productivity. For example take this hypothetical situation: A person would once have to be trained in various tooling skills for assembling a component in a car, robotic tooling is now integrated where their job is restricted to overseeing and aligning the tools. The job is not replaced, however the job is probably susceptible to monotonous environments. The evidence about these environments indicates that boredom is directly associated with negative individual and organisational performance results (Loukidou, Loan-Clarke, & Daniels, 2009). Digital fabrication is much more than replacing people with more effective tools, it is in fact the opposite to this. The real revolution of digital fabrication is bringing programmability into the physical world (Solon, 2013). The digitisation of the fabrication process makes the computer not only describe the output design, but be responsible to create it exactly. This gives more input for the designer from inception to construction. The reality of digital fabrication is not as severe as these opinions suggest. The fact is, Digital Fabrication does not seek to make on site builders, manufacturers or shop floor workers redundant. It offers parallel methods for fabrication outside the norm, offering some benefits with other risks. Moreover, it is not suitable in all situations. People will always be more adaptable that digital processes.

Table 2: Key points of Digital Fabrication Workflows

<table>
<tr><td>Source</td><td>Digital Fabrication Workflow Diagram</td><td>Key Points of Interest</td></tr>
<tr><td>(Aswald, 2016)</td><td>
</td><td>Repeatable Process
Various PC interactions
Output of Physical Model</td></tr>
<tr><td>(Payne, 2011)</td><td>
</td><td>Physical output
Feedback loops
Various phases</td></tr>
<tr><td>(MADLAB, 2016)</td><td></td><td>Visual representation
Simple
Various PC steps
Feedback loop</td></tr>
<tr><td>(Beon Solar, 2016)</td><td>
</td><td>Cycle Process
Fabrication based
Focus on physical products</td></tr>
<tr><td>(Siegel, 2014)</td><td>
</td><td>Interactions between all steps
Indicates cycle process
Feedback is of importance</td></tr>
</table>

2.4.2 Management of a digital fabrication workflows

Digital fabrication workflows and descriptions are as varied as construction methods and tools available to be used within the process. However, there are some significant similarities in the focus of workflow diagrams and flow charts which help to identify key features of what a Digital Fabrication workflow is. The key points identified within table 2 are that a digital fabrication workflow has a heavy emphasis on the physical product and providing feedback through the workflow. There appears to also be a significant similarity to fabrication process models, with processes being defined and assigned hierarchy within the workflow.

Digital Fabrication is a workflow process that provides a contemporary stance on design with a heavy relation to many process and knowledge management ideas. Correct understanding of productivity and efficiency as well as integrating traditional fabrication ideals is essential to creating a good Digital Fabrication Workflow. The one defining trait of a Digital Fabrication workflow is the focus on rapid prototyping and providing a management philosophy to cater for a large amount of communication and feedback through the design process. The large similarities to traditional fabrication allow for management techniques to be integrated into the workflow of a similar nature.

2.5 Knowledge Management & Process Management

The methodologies used to manage workflow development and integration are varied. Amongst these methods are two underlying management principles: Knowledge management, and Process Management. Knowledge management relates to the collection and organisation of data, and the latter relating to controlling the flow of the information.

2.5.1 Defining Knowledge Management

When implemented correctly, Knowledge management can improve Performance by: decreasing production time, cost. Good knowledge management can increase quality through: Avoiding mistakes, reducing rework, making Better decisions (Alshawi, 2007). There are two main approaches to knowledge management: one approach utilizes technology like computer systems and does not fully address the role of people and the work environment. The second focuses on the soft issues and ignores the importance of advances in technology to provide an effective knowledge-sharing environment. Alshawi suggests there is a need to integrate these two schools of thought. "named socio-technical" knowledge management. This is an overcomplicated ideology that in reality can be achieved with good workflow management technique integration. Looking at what has been identified for the development of BIM technologies, recalling the point BIM is not a solely computerized process, it can be argued this integration of knowledge management is already being attempted within the construction industry. Organisational culture is critical to promoting the sharing of skills, resources, and knowledge (Alshawi, 2007). Some organisations do not have organizational culture to allow for Knowledge Management: e.g: employees are accountable for the time and reward system and promotions are based on value added performance, it is rare to find people engage in knowledge-sharing projects if they are not seen as value added (Alshawi, 2007).

The concept of knowledge management has emerged over the past decade to refer to: Acquiring, storing, structuring, and deploying knowledge across an organisation (Alshawi, 2007; Jernigan, 2008). To encourage good and collaborative workflows, information must be readily available over an organisation with users able to access feedback and data from other people in an organised manner. This is what can be defined as good knowledge management. When implemented correctly, Knowledge management improves performance of the organisations workflow. To facilitate good knowledge management practice, top level management should provide knowledge management visions, a strategy, and practice their respective leadership role (Alshawi, 2007). Moreover, the management roles have to provide a strategy understandable by the users to show what the goals, and the process for knowledge sharing is. A simple, common place process for effectively establishing this organisational mind-set is to undergo a work-study:

1. Identify a set of goals to achieve for the organisation.
2. Upper management support and commitment.
3. Understand existing process.
4. Create long term strategy for Knowledge Management to achieve desired goals: Set management priorities, raise awareness, strive to create appropriate infrastructure, establish top-level measurement system.
5. Develop plans and objectives to improve weaker areas with relation to KPI's.
6. Reflection and communication of success and failures.

2.5.2 Process Management

At least 50% of project management is dealing with people and building relationships and by definition we are interested in managing these relationships to the benefit of the project (Fewings, 2005). Basic project management ideas are blanket understandings which apply to all types of projects, however, this does not mean all techniques are applicable to Digital fabrication. Process Management aims to improve the efficiency of the design process and its integration with the construction process (Fewings, 2005). Team work vs Group work is one of the most significant ideas that must be considered in designing Process Management techniques for Digital Fabrication Workflows.

2.5.3 Team and Group management

A group is a number of people working alongside each other, perhaps have little control over their combined output. Whereas a team is a stage further. Members are committed to common aims and are mutually responsible for their outcome. Teams are more aligned to effective project based working (Belbin, 2011). Traditionally in construction, teams are formed of people from different organisations. What concerns the Project Manager is to optimise working relationships and this comes from experience and intuition, but will be helped by an understanding of the individual behaviour and interactions among members. Bruce W. Tuckman in 1965 developed the four stages of group development. Forming, Storming, Norming, Performing. This is set of steps in every group development into a team where each stage has a significant impact on the productivity of the group. The concept of productive teamwork and the existence of teams does not automatically indicate better productivity. Moreover, it is well known that the existence of a team may introduce waste (witness four New Zealander road workers watching one person digging a hole), a new team needs to create a synergy that is more than the sum of its parts to arguable justify its existence. To achieve this productivity increase the idea of Psycho-engineering (refer to Belbin reference for more) where team refers to the knowledgeable use of psychometric methods and motivation to build a robust team which is then able to form good working relationships (Belbin, 2011).

2.5.4 Path to Knowledge and Process Management

Essentially, there is a long road to establish Process Management with 'integrated ways of working' presenting opportunities for reduced waste and adding value. Better understanding of the benefits of an open, integrated design culture are required. The goals here, are to identify the requirements of what an integrated culture will need to survive and influence positively on production within the digital fabrication workflow. Once again, the reflection on what BIM projects offer fit into this discussion. The value of open, central databases for information is significant. Digital Fabrication process management therefore has a direct link to applying management techniques and principles present in existing BIM practice. These include contemporary shared database software's and planning related to programmable parameters during design rather than deadlines.

Ensuring the right quality of building design information is produced at the right time and conveyed to the right people is another principle of process management which applies from BIM to digital fabrication. Design management responds to this need to have a defined and co-ordinated direction for team based projects (Fewings, 2005).

Design is an iterative process, this is a fact and is well documented (Fewings, 2005). It is important to understand the iterative nature of design before you can manage it and give time for reflection and development. In addition to this, efficient information flow is a key indicator for productivity (Stainer, 1997). The correct implementation of both Knowledge management strategies and effective process management is a major factor in understanding and commenting on the performance of Digital Fabrication Workflow effectiveness.

2.6 Categorisation of Process Modelling Techniques

Process modelling techniques can be used both to develop process management systems, and to analyse the processes themselves (Aguilar-Savén, 2004). Within both of these two situations, a visual model is required to describe the process either as a data capture, or a presentation of data flow. When integrated into a group or organisation, it is important to understand that process modelling techniques and tools cannot provide the solution to any problems (Aguilar-Savén, 2004). The sole existence is to aid in analysis and re-design of alternative workflows. Therefore, the capability of the tools used to support effective communication and provide blanket understanding is a large contributing factor to successful integration.

Process Modelling techniques *Adapted from (Aguilar-Savén, 2004)*				Strengths and weaknesses			
				User perspective		Modeller perspective	
Technique	Description	Attributes	Characteristics	Strengths	Weakness	Strength	Weakness
Coloured Petri Nets	Graphical oriented language to design, specify, simulate and verify systems	Network of places and transitions	Petri nets differentiated by visual, hierarchical systems	Easy to understand	Generally excessively large	Possible to create with database roots and well defined software systems	Time consuming
Data Flow Diagram (DFD)	Descriptive Diagrams for analysis	Flow of data	Explain sub-layers	Easy to understand	Only flow of data is shown	Easy to create and verify	
Flow Chart	Graphic Representation	Flow of actions	Generally not sub-layers Great Details No Overview	Communication	Can become too large	Quick to create	No standard methods, different notations exist
Gantt Chart	Matrix representation	Flow of activities and durations	Relate activities to time	Easy overview representation and performance control	Not and aid for analysis or design	Simple	
Object Oriented Methods	Describe a system with different types of objects	Object structure and behaviour	Classified into objects, classes and messages	Control and process monitoring	Excessively large and fragmented data	Internal consistency when using software	Complex, requires large access to data
Rich Pictures	Contextual representation of 'things'	Represent process	Represent some of the 'richness' of the process being examined	Support communication and understanding of the process	Not structured	Easy to illustrate components as people	Lack of standard notation
Role activity Diagram (RAD)	Graphic representation	Flow of individual roles	Detailed view of empowerment no overview	Supports communication Easy to read	Not possible to be decomposed	Includes business objects	
Role interaction diagram (RID)	Matrix representation of processes for co-ordination of activities	Flows of activities and roles	Inputs to and outputs are not modelled. Activity staff are modelled	Intuitive to understand	Important information is lacking	Complex processes can be displayed	Difficult to edit therefore usually created from scratch
Workflow	Facilitation or automation of process	Flow of information, tasks and rules.	Flow of tasks between computers and people	Easy to analyse. Short learning time		Possible to integrate software data transfers	Many distinct visual languages. Lack of standard notation

Table 3: Process Modelling Techniques

There are a wide range of tools available to aid in modelling processes. Of these tools, not all are appropriate for the support and management of integrated projects. Another factor impacting the ability to use these tools is that very few have constant notation languages. The notation language is important for the use of a process after the designer of the system has moved on and to ensure users have a level understanding of the information. Despite the lack of consistency in this area, tools like flows charts and Gantt charts have become common for describing processes and managing dates (Aguilar-Savén, 2004). The clear tool to be adapted to use for managing digital fabrication is a workflow. A workflow, as already discussed, aids to manage the flow of tasks essential to the digital fabrication process. Aguilar highlights workflows as having a large amount of distinct visual languages however typically are presented in a flow chart for simplicity. These allow the graphic hierarchy to actions and rules to be followed with relative ease. For a design process, they are invaluable tools as graphic people are more inclined to respond positively to graphics and flow chart rule sets (Belbin, 2011). Earlier in project establishment phases, RAD diagrams can be useful tools to help an organisation establish and define who will do what are specific project phases. In addition, this tool is also a graphic representation often integrated? into flow charts resonating well with graphic people (Aguilar-Savén, 2004). A tool not identified in literature but common in building information modelling is a protocol. This, much like a workflow, is a set of rules to be followed, guiding a design team from project initiation to completion (BIM Task Group, 2015). Given the similarities between integrated BIM processes and Digital Fabrication, it is not outside the realms of reason to create a protocol alongside the workflow for the use of managing digital fabrication projects.

2.7 Summary of points

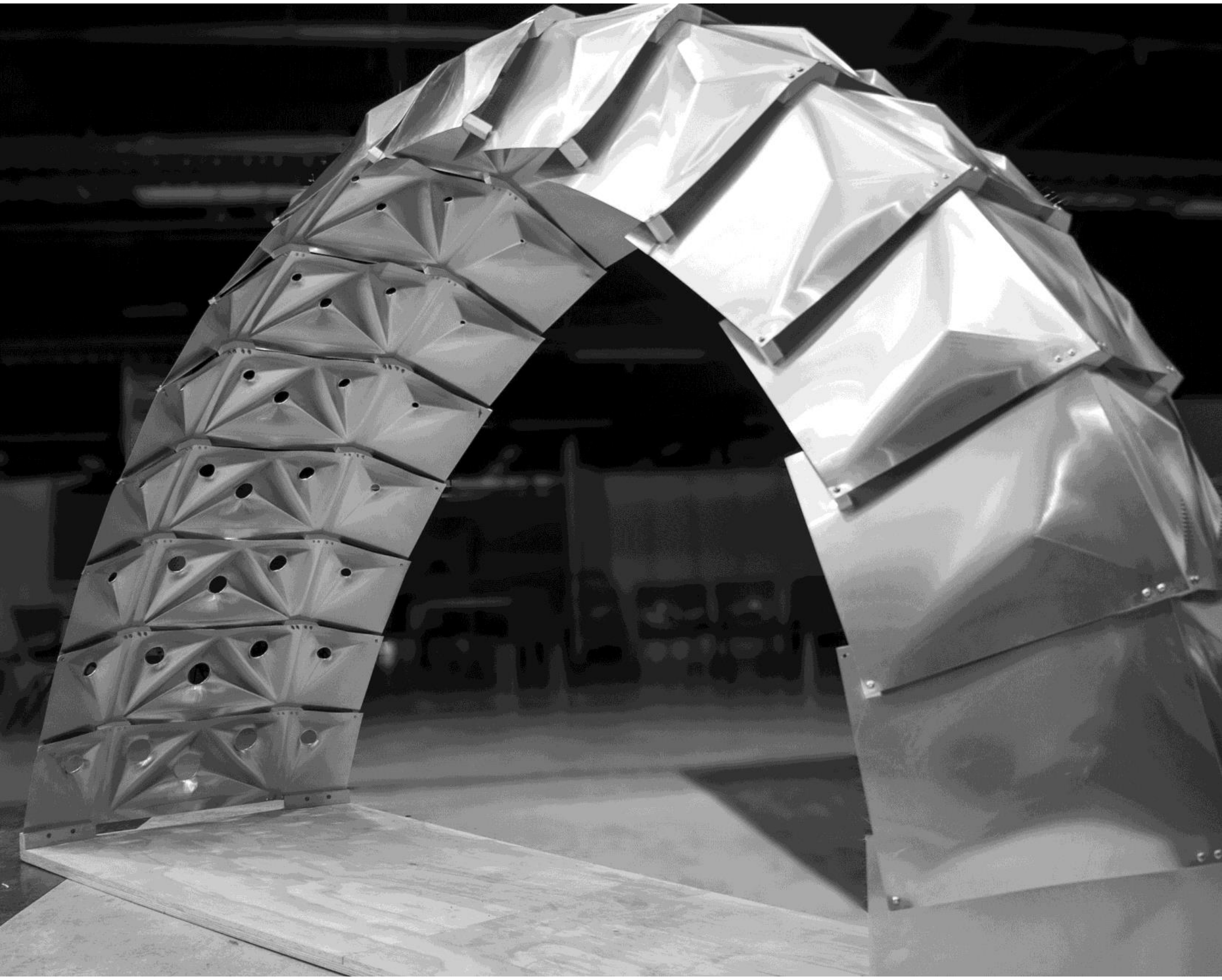
There is a large similarity in management techniques that can be utilised in Digital Fabrication and traditional fabrication, with both focusing on the manufacturing of products or 'things'. Within these there are significant similarities to how integrated BIM projects can be organised and managed. As a result, similar tactics can be implemented. Techniques used in establishing this process and managing it can include:

- Flowcharts
- Gantt charts
- Protocol Document
- Workflow creation and management

A workflow is the organisation of documents, information and tasks to be passed from one action to another. Ultimately, defining a workflow comes full circle and is not helpful in creating one. Through providing a definition, some aspect of what should be focused on is either lost or forgotten in translating it. What is actually most important is very simple; a workflow relates to how an organisation works. The key points in defining performance for a robotic design Fabrication Workflows are:

- Collaborative knowledge management
- Effective Information flow
- Efficiency and productivity are major KPI's

Digital Fabrication is a workflow process that provides a contemporary attitude on design with a heavy relation to many process and knowledge management ideas. Correct understanding of productivity and efficiency as well as integrating traditional fabrication ideals is essential to creating a good Digital Fabrication Workflow. Digital Fabrication focuses on rapid prototyping and providing a management philosophy to cater for a large amount of communication and feedback through the design process is essential in an effective output. Efficiency is the core component of Project Management, Process management, and Knowledge Management. The assessment of are all investigated as part of this thesis to understand what ideas can be applied during a digital fabrication project life cycle.



3.0 Methodology

This thesis has the final goal of providing an effective workflow for integrating digital fabrication into design. As part of this, the tools suggested as most useful for managing this workflow will be based on the results observed at the end of this thesis. The academic contribution is therefore a critical assessment of management in contemporary processes and a framework for what to consider when approaching alternative methodologies for design.

There are no examples of digital fabrication within New Zealand, and very little expertise for the application of robotics. Subsequently, the design team of Think Machine is going through a learning process to understand the use and application of a robotic arm in design. Essentially what this means is that the team is experimenting with the technology and processes as a means to understand what works and what does not.

During this learning process, it is essential that reflection and critical evaluation of actions drives the design decisions of both product, and workflow. As design is an iterative process, there is good ability to work in this way. This assessment and reflection provides opportunity for an important conceptual input for the management of construction processes. However, issues presented suggest that there is a very broad initial scope of work and a high learning curve required which will impact on Think Machines ability to have focused design outputs. As with the design team, the design and development of a workflow is a learning process where there is no clear precedent of how to manage, nor how to coordinate the process. Undergoing a Work Study will provide the best opportunity to experiment various management strategies and tools to find the most and least effective solutions.

A Work Study methodology is identified as common in evaluating the performance of workflows and management processes and has synergy with the design process (R. Oxley & J. Poskitt, 1986). The method takes an iterative approach allowing for the design of systems and analysis of results with clear feedback into more effective processes (Bhatawdekar, 2010). The information gathered for analysis in this research is of qualitative nature, allowing for distinct management perspectives to be commented on and compared to well established literature on the topic.

Qualitative analysis through a work study method, is fundamentally an iterative set of processes (Srivastava & Hopwood, 2009). This process evaluation, much like design is a loop-like pattern of multiple rounds of revisiting the data as additional questions emerge, new connections are unearthed, and more complex formulations develop. Reasons cited for process evaluation and re-design include increasing efficiency of work hours, improve product satisfaction, increase quality of products / services, reducing costs, and meeting new (business) challenges (R. Oxley & J. Poskitt, 1986). Work studies have two main aspects, method study, and work measurement. These are closely related.

3.1 Method Study:

The process of a method study is straight forward:

- Select (the work to be studied)
- Record (the relevant information about that work)
- Examine (the recorded information)
- Develop (an improved way of doing things)
- Install (the new method as standard practice)
- Maintain (the new standard proactive)

The tangible benefits of a Method Study, is the provision of factual data to assist management in making decisions (R. Oxley & J. Poskitt, 1986). Moreover, the method study enables management to utilize the maximum efficiency of all available resources (University of Wisconsin, 2004). By using a Method Study in this research, a fact based analysis of process efficiency can be established. What this enables is the ability to clearly identify the issues introduced into the workflow, and suggest logical improvements to the system. Qualitative data collected in this way can be assessed against KPI's and be used to track how the processes improve over time. Basically a Method Study conducted in this way is used to simplify the work or working methods, thereby influencing Think Machine towards higher levels of productivity.

3.1.1 Recording techniques and methods

Table 4: Recording Techniques

Source	Technique	Examples
(R. Oxley & J. Poskitt, 1986)	Charts	Outline process charts Flow process charts Multiple activity charts
(R. Oxley & J. Poskitt, 1986)	Diagrams	Flow diagram String Diagram
(R. Oxley & J. Poskitt, 1986; University of Wisconsin, 2004)	Photographic / Observation	Photos Film Notes / Reports
(University of Wisconsin, 2004)	Interview	Single Interviews Focus groups

Recording techniques commonly used in gathering appropriate data generally are from an 'inspection' point of view, looking in from the outside. Observation and recording of key processes and looking at the bigger perspective is an advantage that this research will integrate. Moreover, the provision of charts and flow diagrams are invaluable tools when working with visual people (Fox, Murray, & Warm, 2003). The selection of which techniques are to be integrated comes down to what is proven to be most effective. It is possible for techniques to be partially effective which complicates the ability to provide clear guidance as an outcome of the research. Subsequently, observation and critical reflection of each technique applied is vital to understanding the effect it has had to the performance of the workflow.

Think Machines' wider research goal is to understand and establish digital fabrication methods in New Zealand. There is no established digital fabrication workflow in New Zealand, nor a specific method addressing design with a robot. The knowledge gap this thesis fills is a process workflow, and an understanding of what can be achieved with the tool. The Work Study method provides opportunity to develop a workflow which reflects the iterative process designers want to achieve with the tool. Much like the design team of Think Machine, a Work Study utilizes an iterative process and allows the development of management ideas to be synchronized into the greater teams development as research progresses.

3.2 Work Measurement:

Theoretical perspective will be used to analyse observed behaviour and draw from literature on methods to improve efficiency, productivity and quality of processes and outputs. Statistical data cannot be used as it is nearly impossible to measure efficiency when not considering time a KPI. Unlike a manufacturing process where efficiency can be measured by a ratio of inputs to outputs, Digital Fabrication is a design process where outputs are not always quantifiable. This is the management assessment paradigm where, although many aspects are quantifiable in units of time, cost or quantity, the impacts of them in terms of performance within a workflow are not. Needless to say, measurement of performance is not without its challenges in this situation. Many measures of performance do not necessarily capture the quality or productivity, then to be comparable, measures need to take into account hours worked or effort invested into the processes.

3.2.1 The Performance indicators

Recalling the literature on performance indicators, the primary points to be reflected on in this thesis are **Quality, Productivity,** and **Efficiency**. These three performance indicators provide the best ability within the social constraints of this research to evaluate workflow efficiency.

Work measurement is the application of techniques designed to evaluate the performance of a qualified worker to carry out their tasks (Bhatawdekar, 2010). This often utilizes a quantitative measurement of the time taken to perform a task or process thus enabling comparison of effective, and ineffective time. However, time is not considered a key performance indicator in this research and thus this evaluation cannot be completed. Instead, Quality, Productivity and Efficiency will be assessed on qualitative grounds.

3.2.2 Quality

Quality is defined as the standard of something measured against other things of a similar kind (Kumar & Sivanandadevi, 2014). This is a good way to describe how a new product compares to existing ones in a market. For example, a new mountain bike labelled as medium quality is likely comparable to slightly aged model of medium quality. In management, this is a more complicated phenomenon to describe. Better process management is the philosophy which governs quality in workflow performance assessment. Using the definition of quality, a comparison of similar things will be used to compare existing workflows against the first workflow. Later iterations of the workflow can be evaluated against their predecessor thus providing insight into what changes in focus have significant impacts. Qualitative discussion and reflection on how each manage the flow of information during the process is the focus of these discussions. Quality can be discussed with relation to quality assurance, control and outputs. Moreover, a discussion of avoided mistakes, reducing rework and making better design decisions is required to analyse the quality of the workflow.

3.2.3 Productivity

Understanding the function that project management has for workflow establishment and control is the core topic for discussing productivity. Productivity can be analysed in many ways, generally investigating the ratio of inputs to outputs in terms of effort. Productivity performance of the workflow will be determined by discussing the procedures implemented and how they influence the workflow processes. Critical judgement is crucial for these discussions as they will provide the best lessons moving forward to provide clear momentum for Think Machine.

3.2.4 Efficiency

Efficiency is heavily tied into the discussion on productivity and together these KPI's form the majority evaluation of effectiveness. Good workflow management should lead to higher degrees of efficiency and productivity which is what makes the clear separation of these three KPI's difficult. The flow of information in digital fabrication is the core principle that enables rapid prototyping. As such, the performance of the workflow is restricted to discussing how well this flow of information functions. Observations of confusion, lack of motivation and deference from suggested processes would suggest poor performance in terms of efficiency. They suggest the flow of information is either incorrect, or poorly managed. Discussion of efficiency ultimately displays the issues and strengths of any workflow and thus is the primary focus of this research method.

3.3 Limitations of this research

As the research is conducted within an educational social environment there are large variations from standard practice in day to day activities. This variance, has some impact on the effectiveness of tools, the ability to measure performance in terms of financial evaluation, and the inability to measure and associate time savings. The effectiveness of workflow implementation and the ultimate success of the project therefore relies on critical evaluation rather than quantifiable measurements. As a result, the outcomes are limited to a framework of ideas with quantifiable measurement of performance to be outside the scope of this thesis.

In addition, team members are learning tool proficiency increasing over the period of study. This limits clarity on the effectiveness of implemented tools making discussion of perceived improvements unclear. Despite this, improving proficiency and deepening the understanding of material, benefits iterative process studies and in this case introduces additional perspective and experience (R. Oxley & J. Poskitt, 1986). Effectively, there is little to no impact on the results of discussion as large perceived leaps in understanding would be observed and noted as important contributing factors. Additionally, current industry processes do not account to manage the gradual development of skills beyond the notion of assigning workloads suited to people's capabilities. Ultimately, the development of skills outside of understanding workflow performance relates to design performance, and although related, falls outside the scope of research in this thesis.

3.4 Methodology in Summary

The methodology involving the development of prototype methods will be designed to cover qualitative aspects of performance not generally discussed in management of business processes. However, when discussing the quality, productivity and efficiency of implemented strategies the fundamental link between the three will be discussed with relation to real issues and solutions. The first milestone of research is to establish key precedent ideas, and suggest starting points for Think Machine. From this point on, the management role will be used to suggest improvements and provide critical reflection on the performance of the project workflow. It is a fundamental component of this research to integrate iterative performance assessment techniques to critically evaluate these KPI's. Although quantifiable methods are not established there is a great opportunity to discuss and suggest strong workflows and supporting arguments. The key to success in this research is meticulous observation and recording of how people in Think Machine respond to different techniques and understand why management techniques are successful or not.

Essentially the final contribution to knowledge will be a prototype workflow methodology for digital fabrication based on critical evaluation of Think Machines' processes. Ultimately, the product workflows detailed in this thesis will have limited applicability to direct uses outside of Think Machines' work methods therefore cannot be considered a final workflow. However, a critical output of this research will be to define the requirements of similar processes and suggest a framework for these types of projects in the future. This final recommendation seeks to address the initial research question of how project management can improve team focused design.

4.0 Description of Results

The greater research project for Think Machine can be divided into four main phases of development. Each phase, represents a different stage at which the workflow and methods applied have been adapted or changed. Each workflow is constructed based of the changing design project outputs, and the lessons learnt from previous phase's observation. During the initial exploration phases, the widest set of techniques have been applied thus widdling out what are effective in the situation and what are not. The later phases generally focus on integrating good iterative design management and deal with issues presented in assessing workflow effectiveness. Project Management is integrated from early stages in the design research process. The plan from the start of research is for project management to eventually step to the side and allow the design team to utilize a final workflow with no further development. In doing so, final judgement of the success of utilizing the method is discussed with any further topics of research and development suggested.

4.1 Think Machine Project Process

4.1.1 Phase One Exploration

Phase one, the explorative stage of research is vastly different from the latter phases. As very little has been established for what design outputs are possible, it became very clear that a method to categorically test machine outputs was needed. To facilitate this experimentation, common organisational techniques such as Lists and Spreadsheets have been used. Workflow development at this early stage included facilitating and managing these lists and providing some key milestones to deliver tests by.

4.1.2 Tatu

The second part of phase one is a pavilion project named Tatu, intended to display the material possibilities of working with a robot. Techniques integrated into managing a more focused design output include the original data lists and moved into more time management with milestones and Gantt charts. Visualising the workflow methods through a flow chart is a key process which helped Think Machine to work cohesively in a team environment. At this stage of the research, each iteration is heavily output focused, therefore reducing the need for using tests to identify if design outputs are predictable.

4.1.3 Phase Two Panel System

Moving into the second development phase of research, the design output is reduced in scale to an interlocking panel system. The reduced scale puts more emphasis on output focused iterative design and streamlining the processes of design. Physical outputs and material tests focus more on utilizing fine control of robotic functions with a reliance of parametric modelling to define key limits and constraints being discovered. Subsequently, techniques to manage and coordinate workflow development take key ideas from phase one with new ideas on how to integrate more effective working processes.

4.1.4 Phase Three – Last implementation

The final phase of research for Think Machine, builds on previous systems and completes a pavilion based of the system. The final workflow established is built from all previous lessons and revisits how the team environment works. A major step during the final phase of development is the project management role being separated out from the team completing separate work. Essentially, the goal was to test the final workflow with no interruption or alterations.

4.2 Reflection of Management tools

Strategy	Effectiveness	Failures / Issues
Budget	Useful for planning scale of projects. Usefulness varied	Was not sufficiently integrated into the workflow creating issues with inconsistencies as time progressed.
Fabrication Reports	Organised experimentation period	Often neglected when not pushed by management
Gantt Charts	Useful for milestones	Design team does not use
Lists	Very useful in collecting ideas and design thoughts	Can become disorganised when not recorded
Protocol	Not integrated into observations	
Reporting	Great for establishing understanding of group individual goals.	Once working outside workflow began reduced usefulness of reporting - Independent goals become unclear - Wider team unlikely to read other people's reports
Week Meeting	Successful in establishing milestone goals	Informality reduced frequency and lack of reporting goals established

Ultimately, the integration of management tools is to foster better performance than would otherwise be achieved. A part of this is improving the quality of process by reducing the amount of mistakes and rework that would otherwise exist. Each tool has a specific function and all have a place in workflow management. This however, does not justify the complete integration of all at once. This research highlights that over complication too early in a design environment tends towards confusion and poor ability to effectively complete tasks.

4.3 The Workflow

4.3.1 Process of assessment

The following sections define and evaluate workflow performance throughout each of the phases of Think Machines research. There are three key developed workflows developed with a final developed prototype following the three evaluations. Each section will first breakdown the key goals for each workflow and identify the key techniques and tools utilized. Part of this can include responding to previous issues and benefits identified. A process flow diagram will be used as the main tool to display each workflow. Each workflow is broken down into descriptions of process and key function before then being analysed against the KPI’s listed within the methodology. This section presents the facts identified through observation and provide a clear prototype workflow for future development and integration.

4.4 Workflow One A (exploration)

The start point for developing an initial workflow and management processes is in reality the step before the actual establishment of the workflow. First, the identification of what is most important without addressing all possibilities. The first major points to integrate are influenced directly from literature. These are, to facilitate iterative design, define the roles required by the team and manage the flow of information over projects. The main issue to address during this initial step is the lack of understanding around the process, therefore facilitating learning is an essential component to developing initial points to establish workflow management strategies. BIM management processes are used as a precedent here and similar philosophical understandings on what type of design interactions to facilitate are adopted.

Management techniques implemented within this stage of research include:

- Gantt Charts
- Lists
- Software management program
- Communication software

4.4.1 Gantt Charts

Gantt charts are a useful tool for planning and scheduling projects. The most significant issue with using them, is the fact the design team shows little interest in attempting to utilize them alone. After first providing a team access file system, members where encouraged to utilize the Microsoft Project Gantt chart to check progress in assigned tasks. Individual prioritization and personal preference resulted in no incentive to actually use and update this file indicating that in reality, although very useful for plotting milestones and tracking progress, team members do not instinctively want to use the tool.

4.4.2 Lists

Instinctively, one of the first files created by Think Machine was a list of possible design outputs, managing the information after this however is interesting. The idea of saving the information in a single place rather than allowing each individual designer to proceed on separate paths was useful in coordinating the teams efforts. However, access to and readdressing the list was useless. After some time, team members only occasionally utilized lists after their creation. As a designers tool, lists seemed most useful within team meetings as a means to clarify the individual direction of each person. Post meeting, the lists were manually entered back into a database under the original list to show what progress was made over the period.

4.4.3 Software management program

Catia, was the initial software suggested as a design interface with the robot. A part of this included access to the management software ENOVIA. This tool is designed to coordinate files and information created in Catia much in the way a BIM coordinator may organise and database 3D Cad files. In addition, ENOVIA is designed to provide a platform for project managers to interface with a project team and track progress. Essentially, this platform promises to consolidate all project management tools, including Gantt charts into one software package. The implementation is not as simple as anticipated. The fact is there is very little training available and a large learning curve to see tangible results. The integration of ENOVIA into Think Machines workflow management strategies was abandoned due to this barrier. Ultimately, the design process moved out of Catia for the most part to favour other design software.

4.4.4 Communication software

Early on, Think Machine needed a professional, traceable method to communicate and organise design ideas. Slack, an online messaging tool is used to coordinate and consolidate ideas and foster the sharing design culture suggested to benefit BIM processes. The software is both usable on a PC, and mobile phones meaning that all team members could communicate ideas while away from their desks. The software is good at fostering healthy team environments. There are no significant issues to the use of slack, however, the integration does not improve how team members interact with other tools such as lists or Gantt charts.

4.4.5 Points for Initial Development

Issues with the base performance of the team relate to a lack of productivity, and poor quality management. Outputs of the workflow are generally not as focused as intended with decisions on progression not well documented or discussed amongst the group. As a result, the quality of outputs is affected negatively. This does not relate to the physical state of outputs, but the fact useful design knowledge is not captured and used to inform future design iterations. Furthermore, the actual process of gathering and recording data is often skipped. The integration of data management through lists and spreadsheets is not fully utilized. Speculation would suggest that the process involved is outside the realms of "standard" design process and thus not seen as important by team members. To build on this, the workflow must foster a better understanding to how people progress through a project.

Summary of points to address in further development:

- Tools are utilised by the manager, not the team
- Team members are unfocused in design approach, not focused on singular goal but all fighting for their individual outputs
- Communication is strong, but understanding who needs to know what is not addressed.
- Quality of design process is low

4.5 Workflow One B (Tatu project)

The Digital Fabrication workflow must foster a better understanding of iterative process and provide a method to better organise information. First, the workflow begins by requiring a list of requirements. This list will set out the goals and initial ideas from which a design team will progress from. Essentially, this is the project scope defined in a single, simple document. The overall project process should move from concept design into physical development iterations before creating a final (physical) product. This is the same as any other fabrication process developing ideas based of previous lessons.

The fundamental step in this process, comes directly after the initial creation of scope. This stage is labelled 'Digital Fabrication'. This is where the previously established ideas are transferred into digital models, simulated within a digital environment, and then moved on to creating physical tests. Basically, within a simulated space, the physical movements of the robot can be predicted and visualised before moving to a physical test. This is fundamental in both rapid prototyping and safety. In terms of rapid prototyping, the design team is able to understand how they are coding to operate specific movements, predicting how the tools responds to specific movement types. This leads onto the ability to predict if the tool may contact itself, or the tool jig causing damage. The simulation process not only provides this additional step of testing, but it provides an opportunity to gather additional useful data. Safe, or 'passed' tests are recorded into a database filing system which includes the saved program file, and a description of the test. Through saving this, older programs can be located, and adapted to new uses. This is similar to how in BIM design processes, often existing libraries of 3D CAD files can be used to populate projects rather than create entire new models.

The final stages of the workflow include organising and reporting on the successes and failures of the tests before feeding back into the developed concept and final product designs. The aforementioned database, is used to coordinate this information in the way of fabrication reports. The report consists of a simple description of parameters and the results of testing. This fabrication process, is designed to cover one week cycles where at the end of each week, the fabrication process and ideas moving forward are collected, and debated on. The goal of these meetings is to refocus the group back into a singular goal previously identified as a key reason for poor performance.

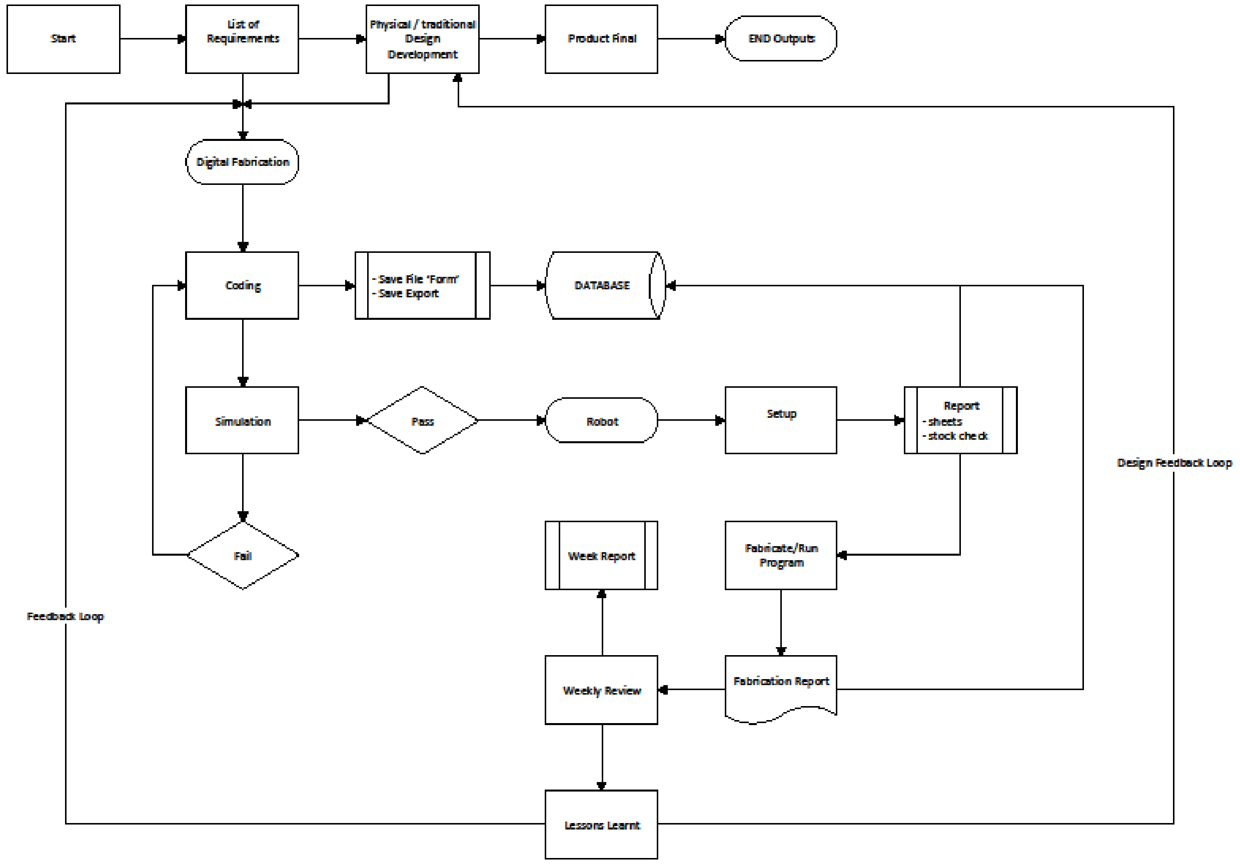


Figure1: Initial Workflow visualised as a flow chart

The tools used in this workflow include, lists, Gantt charts, flow chart diagrams and has kept the existing communication software. The primary issue identified that needed to be addressed in this workflow is the lack of adoption of tools to help manage the process by people other than project management. In addition, the lack of any singular focused design hampered group project development resulting in a low productivity and quality of project outputs. Firstly, the integration of a flow chart to visually display how project management wanted to control the process is extremely useful. Communication of the reason specific order is needed is widely understood and agreed upon. The workflow at this stage is detailed, has the ability to track progress of people using it and has a short cycle. All of these points indicate a strong resemblance to traditional fabrication and are initial indicators to good productivity. Tracking progress enabled Gantt charts to be updated and milestones shifted based on the scope of work required. It is worth noting, that the design output at this stage in research is heavily focused on a pavilion somewhat reducing the scope of initial ideas. Comparing Gantt chart milestones, against tracking of users within the workflow, although used mostly by project management, is very useful as a communication tool during meetings. The time required to finish Digital Fabrication tests can be estimated and provide information to scope changes necessary to meets final milestones. Without the integration of time, via milestones or identification of how long each step is taking in days, there is evidence suggesting people do not move forward at sufficient pace required for rapid prototyping. The most significant aspect of this workflow to be successful, is the clear focus on iterative design and feedback from each fabrication run. Essentially, this forces designers to think about what is good and bad about their design.

Overall, this workflow is not successful in facilitating many of the desired points and has significant shortfalls despite the success of others. The workflow doesn't reflect the reality of how architectural graduates design in this situation. This workflow has a strong focus on iterative design, and creating many different prototypes, however the team is working on a focused singular output. Think Machine in reality, focused on the initial ideas and scope of a design, then focused on a single large output (Tatu). The data basing goal is not achieved as simply, it is not used as intended. The file becomes a drop point for design files and has little governance nor ability to categorically separate information. Furthermore, expanded datasheets for storing test ideas categorically became redundant due to the pace at which new ideas are created and scraped. The implemented tools are not all utilized in the intended way. Subsequently, this lead to unproductive work environment with poor coordination of information. Ultimately the process is not efficient as very little of the desired tools work in a way that is effective. The workflow does not capture the core ideas of iterative design and managed information flow.

4.5.1 Summary of Observations

Table 5: Positive and Negative Observations for the base workflow

Positive	Negative
• Sufficiently Detailed • Tracking of progress • Designed on a one week project cycle • Based from existing fabrication workflows • Physical lists integrated to help manage panels. • Workflow visualised in flow chart • Gantt chart worked	• Doesn't reflect the reality of how people constructed final design outputs. • Database idea not fully utilized. • Did not begin in reality with a 'LIST of ideas', design team came up with design which was then the focus point. • Lessons learnt not utilized although they NEED to be to make this iterative process. • Expanded Data sheets – team moved away from their use as became irrelevant too fast • Output focused • Process mistakes

There are significant issues with this workflow. Overall, the document is not followed and users stray from how the flow chart defines working processes. Essentially, this workflow is a great goal, but does not currently reflect the reality of how people construct final design outputs with digital fabrication. Moreover, this workflow does not clearly define the roles of each person of Think Machine. Providing role specific tasks would reduce the wide variation in ideas confining each user to independent parts of the project.

4.6 The Second Workflow

The second iteration of the workflow has similar roots to initially drafted however generally has a more stripped down approach, streamlining the process. As with the previous version, the workflow starts with a list of base ideas, redefined to base parameters. The parameters include limitations of the final design goal, but no detailed discussion of physical elements or function. The notable similarity in portraying the workflow is a flow chart. This is proven to be the most successful method to discuss and present workflow related ideas with design team members.

The workflow has two major pathways, Ornamentation, and Joinery. These two pathways address individual perspectives in the wider research team whilst also separating out the work into specializations. It is important to note, this workflow is being developed for specific project outputs and therefore despite initially having no detailed discussion on what the output may look like, there is a general consensus that it should be a shading system or pavilion. As such, each person is developing ideas in parallel which have unison. The initial steps of the workflow intend to keep each individual separate to maximise idea generation and reduce confusing ideas and tests with each other. As both the design pathway and joinery progress, a key definable milestone must be met. This is the collection of design ideas consolidating the design parameters. Final research specializations focuses on the use of these parameters for the remainder of the design process. The idea is that all parameters for design are collected at a single point and then must influence the outcomes of the other design processes.

The fundamental idea of iterative design leading the development of ideas is to facilitate a strong process quality. The organisation and visual presentation of the workflow define the outputs as design prototypes which have a feedback loop directly back to the first stage. The idea, is that after completing a cycle, feedback should inspire further development of parameters which respond to issues discovered in experimentation.

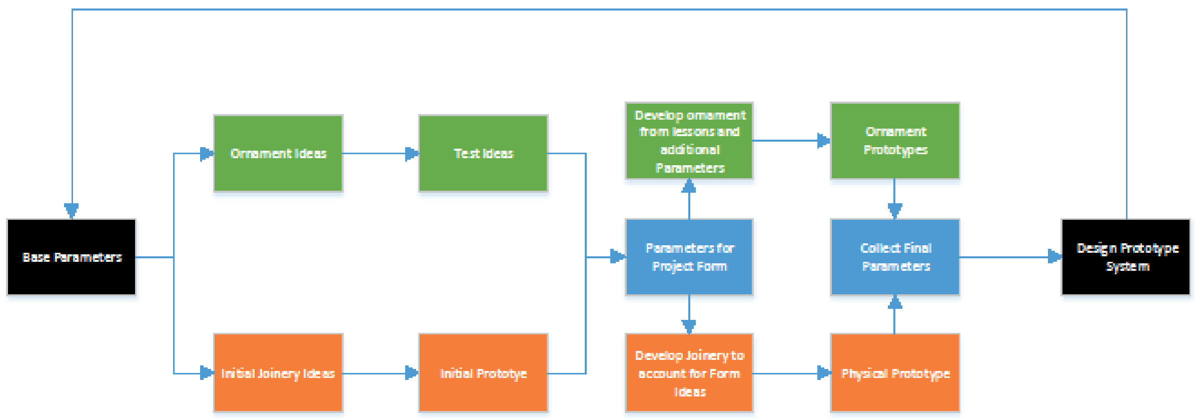


Figure 2: Developed workflow

Ultimately the workflow varied from the intended process to being more direct and output focused. A three week process is established dividing the workflow into concept development, parameter and design development, and final design prototype.

The flow of information is well defined in this workflow from the start, with a clear understanding of what needs to be achieved and at what time. Gantt chart integration became less useful at this stage with the predefined week requirements more useful than individual task tracking. Essentially, there is nothing to gain by tracking the individual time and tasks being undertaken as the scope of current ideas changes too rapidly to effectively gather and assign milestones to them all. The only key times are completing weekly tasks. Despite this, the initial step becomes flawed. Not only is there a disincentive to define every specific task, a previous issue, there is no incentive to develop lists of ideas and test more than one of them. There is a catch twenty-two in that allowing more freedom in selection of base parameters, each individual selects a small group and does not proceed past that stage developing them. An observation made during week one of the workflow integration, shows that this first stage led to large confusion and unfocused design. Ultimately, the streamlining of workflow detail has a negative effect on controlling a design process. The fact is information created during the early phases of design needs to be more controlled otherwise the flow of information is severely impeded. The flow of information in digital fabrication is the core principle that enables rapid prototyping. Moreover, the lack of detailed requirements causes confusion in what is actually needed to be produced along the different stages of development.

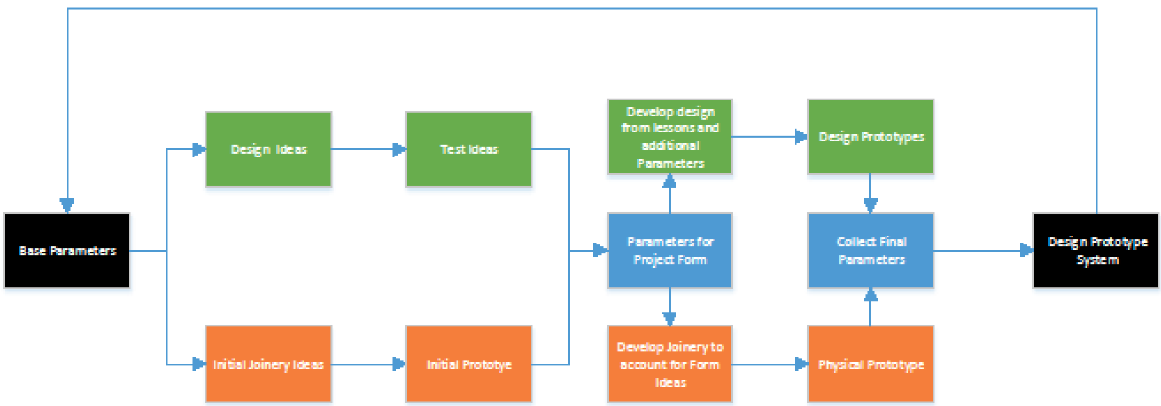
The collection of parameters is an oversimplification. The collection of information does not occur as intended in part due to the nature of the research team working in close proximity. Each member knows what the other is doing, therefore is already accounting for the others work. However, this does not write off the task as a failure. The formal collection of ideas from both ornamental and joinery is a useful exercise in defining how each separate design process works into the other. The list produced as well as design graphics demonstrate how ideas become more developed as the process advances. The use of simple management techniques such as these lists, and visualisations of the process are what best organise team coherency. At this point it is clear that over complication of detailed management jargon negatively impacts understanding. Moreover, it impacts the ability to translate the changes made into tangible improvements in workflow efficiency.

4.6.1 Summary of Observations

Table 6: Positive and Negative Observations for the second workflow

Positive	Negative
• Physical output focused • Reduced scale • More focus on robot control • Gantt chart useful for PM • Streamlined process • Focus on facilitating design	• Stuck in Base parameter process • Lack of detailed requirements • Low Productivity early on • Outputs become a result, not a design • Gantt chart becomes irrelevant • Lack of defined outputs at each step

The key lesson from observation of this workflows integration is that more focused direction and explanation is needed to convince a design team to utilize the correct methodology. The initial stages of the workflow are especially susceptible to low productivity due to the lack of focus on correct information flow. Subsequently, both the efficiency and quality of the workflow are negatively impacted. An overarching issue with the workflow to this point, is that the design team become too focused on end products rather than approaching design with iterations in mind. A Digital Fabrication workflow must foster iterative design at the core otherwise the ability to rapidly alter designs becomes wasted opportunity. This reflects poorly on the effectiveness of the Digital Fabrication workflow.



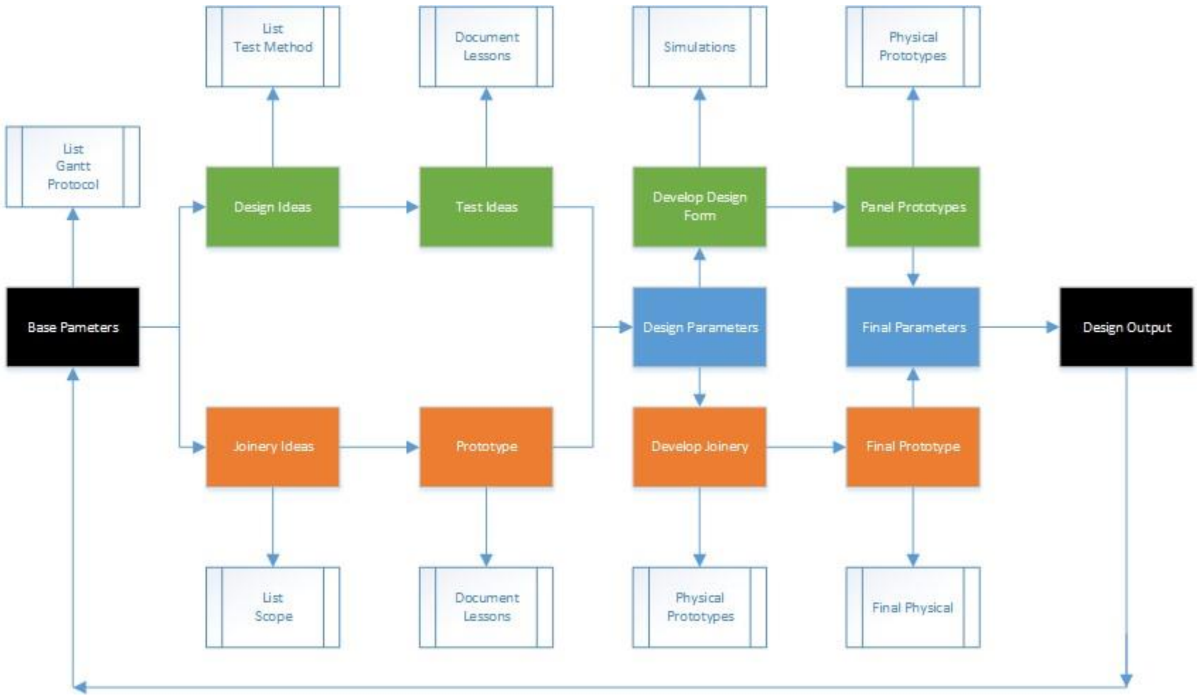
During the mid-phases of this workflow experiment and observation, one member of Think Machine left. As a result, terminology is altered and the base goals to foster ornamentation is removed. As a result, design becomes a very linear process focused on establishing a structure and integrating some basic form parameters. The resulting output is a smaller scope than originally intended however the issues identified with the workflow remain.

Despite the changes made from phase one into phase two, some of the key issues remain. The way processes are completed does not line up with how the workflow is defined. This is in part due to a lack of understanding to what is actually required. Moreover, tools such as databased lists and lessons learnt are not used outside of meetings. These points indicate that the flow of information and the understanding of how one persons' work is integrated into anothers' is not well defined. Most importantly, the quality of design process is hampered by the fact there is no significant evidence of iterative design taking place despite the focus in developing workflows which require it. The effectiveness of using flow charts however, is very high. A flow chart has consistently been able to convey management ideas to the design team and physical copies can be referred to whilst working. Moreover, the major issues of workflow performance relate entirely to poor adherence to process. Techniques and tools designed specifically to order process and guide teams are needed in earlier stages of the process to foster the best collaborative team environments.

4.7 Workflow Three, A Proposed Framework and Tool Set

The final revisions of the Digital Fabrication workflow address the last major issues by providing a framework for what needs to be implemented. A lack of early productivity, general poor adherence to the discussed process, and lack of interaction with key tools integrated. Generally, the streamlined approach is an effective way to illustrate the workflow despite the fact to little initial direction is given. To confront the primary issue, three documents are created at the initiation of a project. A list of ideas, a Gantt chart planning the 3 week cycle, and most importantly a protocol document. The protocol is a formal acknowledgement and process guide for the design team to follow. This document targets the lack of coordination found in early stages of workflow progression during the previous research phases. A significant impacting factor to protocol integration is the manner in which it is provided to the design team. It is clear that large documents and detailed additional paper work cannot be integrated as effectively as other tools in this environment. However, integrated via visual charts, a protocol can provide a frame of reference for design teams.

The workflow retains the two major design pathways suggested to foster independent design, and retains an focus on collaboration of ideas at later stages of the design process. However, it is of great significance to the overall performance of the workflow that at this early stage, ideas are shared with feedback drafted into the protocol document. By fostering initial agreement of ideas, the collaborative nature of the project is better established. Looking at phase two's performance, the lack of collaborative work in the early stages lead to significant issues when integrating ideas later. Moreover, the workflow must have clear deliverables at each stage to foster efficiency. A part of this is a clear definition of scope early on in the project. Testing of project ideas is a consistent point of issue through assessing effectiveness of the workflow. The process ultimately has to lead towards a focused design output therefore the way in which people communicate in this environment must be addressed.



4.7.1 Recommended tools & techniques utilized within this final workflow

Flow Chart	- Most effective visualisation tool for a workflow
Gantt Chart	- Use to define milestones - Use to manage early project stages
Lists	- Effective to organise ideas - Effective to organise information
Protocol	- A requirement to better facilitate team cohesion - Risk of over simplification
Role Definition	- Essential to differentiate individual specialization

4.7.2.Gantt charts

Although time is not a KPI for evaluating the effeteness of the workflow, time is an essential component to manage the productivity of a team. Without aggressive milestones and assessment of how people are progressing through the workflow, there is no incentive to move to the next step defined in the flow charts. This tool is best used near the initiation of the workflow to help establish early milestones pushing for productivity. Ultimately, this tool is effective for the management of workflows by the way of highlighting priority processes and defining project milestones, which addresses issues identified with low drive to progress past establishing base parameters. Beyond the use as a project management tool however, a Gantt chart has no use in the workflow.

4.7.3 Flow charts

This visual tool has shown the most positive response when used to showcase how the project team should advance. The issues with flow charts for defining workflow processes are that there is a risk of being both too detailed, and not detailed enough. This thesis has observed that although a clear winner in user appeal, very little can be done with it to ensure correct process is followed. Essentially a flow chart is only a visual aid to help establish an understanding of process. Other tools have to be integrated in parallel to foster the correct working environments needed to establish a Digital Fabrication workflow.

4.7.4 Lists

Essentially, every early step in the Digital Fabrication workflow involves discussion on what to do, and what the scope of work should be. This ranges from establishing base parameters to assessing the performance of basic test results. The only way to clearly consolidate the findings is to list them. Attempts to facilitate data basing and spreadsheets have failed. In some situations, reports on the physical fabricated panels yielded some success, but ultimately become useless when the process is observed with no interference. The fact is, writing out a list of ideas, or success and failures is what has allowed people to make the best design decisions and move effectively through the workflow steps. The only inhibiting factors to this progression is where other tools and techniques are not used and cloud the flow of information.

4.7.5 Protocol Document

A protocol, is much like a workflow in its own right. Essentially this is a formal document that explicitly states the steps and process order required to complete a project. Widely adopted in BIM projects, this is a useful tool to clarify processes and tools. The issue with integrating a protocol into this specific situation, is the track record held by Think Machine for not utilizing additional documents. For future developments of Digital Fabrication workflows, establishing a protocol for project initiation and facilitating the other core tools through the early project phases is a must.

4.7.6 Efficiency of the workflow

As defined, efficiency is heavily tied into the discussion on productivity and quality. Without effective performance in all three, a workflow will have issues. Good workflow management should lead to higher degrees of efficiency and productivity with the clear establishment of processes directly correlating with higher quality workflows. The flow of information in digital fabrication is the core principle that enables rapid prototyping. As such, the performance of the workflow is restricted to discussing how well this flow of information functions. Observations of confusion, lack of motivation and deference from suggested processes have suggested poor performance in terms of efficiency at all of the observed Think Machine project phases. However, the integration of various project management skills and techniques has indicated that project management has the position, and the ability, to better direct a Digital Fabrication workflow.

5.0 Discussion of results

When implemented correctly, workflow management can improve performance by: decreasing production time and cost; and can increase quality through avoiding mistakes, reducing rework, making better decisions (Alshawi, 2007). The actual implementation of workflow management techniques has had various impacts on the effectiveness of a Digital Fabrication workflow. What is not clear through observation is why mistakes and better decisions are not generally seen despite attempts to provide better process management.

5.1 Team development

Tuckman's' four stages of team development, forming, storming, norming, performing applies to the development and productivity of all teams. There is a significant effect on team productivity as a team progresses through each stage (Macpherson, 2015). This effect is not quantifiable however dates of work and goals are consistently not met within all versions of Think Machines workflow. Plans are made and not respected, and the research priorities shift during thesis study with team members not aware of final output results until later into studies. All of these points not only stress other members responsibilities but have direct impacts to productivity and efficiency. In reality, this is how teams work, with different roles and different priorities shaping project outputs.

Misconception	Reality (Belbin, 2011)
Team Roles are measures of personality	Team roles are functions of the different demands made on team members if the team is to become effective. Individuals respond to these in different ways.
People cannot change their Team Roles.	While individuals will have a certain affinity for certain team Roles and less for others, in all cases learning plays a part. Hence some degree of adjustment is always possible.
Team Roles vary with culture.	The basic types of Team Roles contribution have been identified in all cultures. BUT the manner of their expression depends of social customs.
People in some types of society cannot adapt to Team Roles.	The structure of authority sometimes makes it impossible for Team Roles to flourish. But once tyranny is removed, new personal growth possibilities arise.
People should be encouraged to overcome their weaknesses to allow them to perform well in each of the Team Roles.	Strong performance in one Team Role makes it quite likely there will be a weaker performance in another. It is more important to perform certain Team Roles well than to cover the whole range where the effects would be to deny Team Role opportunity to others.

5.2 Initial Workflow Development and Tatu

5.2.1 The literature defined workflow

The first attempt at creating a project utilizing a Digital Fabrication, showed poor workflow performance. There are many explanations which could account for at least a part of the poor performance and is likely that in fact more than one of the issues are responsible. Aside from the fact workflow documentation was not generally utilized as intended by the design team, many other points can be examined. It is arguable, that the initial scope of the first project was too great when considering the lack of knowledge in how to both use the robot, but also facilitate a good design process.

5.2.2 Project Scope

Of the issues, scope is a standout topic. Given the research scope of developing larger physical systems, and the complete lack of existing workflows to base the design process from it is very likely that the initial scope of work was not manageable. Looking at the negative reflection of the first workflow, key points to extract include that the workflow and processes suggested don't actually reflect how the project was completed. Furthermore, after suggesting a systematic approach to exploring the material possibilities reflection shows that the process was not followed as intended. In addition to this, attempts to further develop the system to facilitate a more organised, expanded database received significant resistance from the design team. Essentially, the more formalized the process became the less effective people would respond to interacting with it. With the added effect of an undefined scope, productivity is significantly impacted during the early stages of research and design. If a more formalized and systematic approach could have been successfully implemented, a clearer trail from test to test would be present. As a result, there would be a significant positive impact on the Quality and Productivity of the digital fabrication workflow. The poor acceptance and ability to integrate these management tools into standard practice for Think Machine can be attributed to a portion of reduced productivity. However, the inability to integrate basic systematic organisation here is not entirely at fault. Key documents such as 'Lessons Learnt', the initial representation for a feedback loop although drafted, is never clearly integrated and utilized to actually inform design decisions moving through this workflow. Essentially, this workflow is a great goal, but does not currently reflect the reality of how people construct final design outputs through digital fabrication. It is possible that peoples changing opinions on how the process should work, and a lack of utilizing tools on offer, have a large part to play.

5.2.3 Added Value and Collaborative Work Environments

The similarities between holistic understanding of Digital Fabrication and Building Information Modelling have striking similarities. Namely the core focus on facilitating collaborative design environments. Subsequently, the most effective communication in this work environment grants the ability to solve problems (Hardin, 2009). This focus on facilitating effective communication embodies the idea of efficiency. In addition this can be considered a value added process, where strong professional relationships and better communication lead to both improved design decisions and less design re-work. There is a flaw in existing delivery methods where team members have little incentive to create additional value as they are unlikely to receive additional compensation (Hardin, 2009). This is exasperated when then considering some practices are paid based of total project cost, therefore creating savings would actually earn less revenue (Hardin, 2009). The point here is that people have very little drive to actually participate in additional work to facilitate design improvements without direct benefits to themselves. This is not unexpected nor can it be analysed within the social group of Think Machine. However, it does raise the fact that despite attempting to create a collaborative work environment, people will naturally have no drive to create additional work for themselves. In this case, added value would be directly equitable to improved quality performance. Ultimately, the initial workflow displays poor performance in all three of the Key Performance Indicators. There is room for improvement in both the management of information, and also the accessibility of useful tools to guide the process.

5.2.3 Critical evaluation of performance

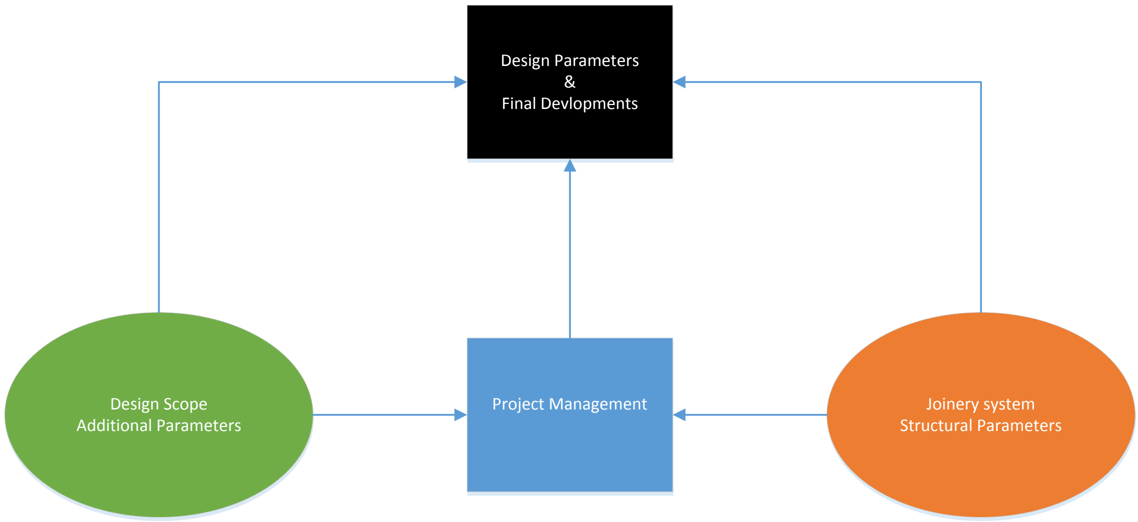
The initial Digital Fabrication workflow is not an example of an efficient process. There are significant productivity and quality inconsistencies which negatively impact on the effectiveness of the workflow. The flow of information is not clear as evident by design ideas not reflected on through lessons and multiple passes of the process. The lack of success in team members utilizing key management tools is indicative of the workflow performance. The fact that the tools are not utilized indicates a lack of controlled process management required to foster good design environments. It is clear that the workflow is not facilitating the actual use of tools therefore design team members are left on their own in terms of navigating the procedure. Perhaps it is unfair to outright say the workflow is ineffective, as at times tools are utilized as expected, generally providing a good indication of productive activity. However, tools such as the databases and spreadsheets always became irrelevant after time. In reflection, a large amount of factors impact the effectiveness of this workflow. Poor productivity is a large factor, as is poor management of processes leading to generally low efficiency. Moreover, there is a significant negative impact for workflow performance caused by design teams focusing on singular outputs such as Tatu. A singular output does not foster good working environments for iterative design. This is abundantly clear in observations of Think Machines utilization of tools and adherence to the workflow process itself.

5.3 The Developed Workflow, A Panel System

After analysis of the issues with early development of workflow ideas and performance indicators, it is abundantly clear that over complication of workflow processes has negative impacts to workflow effectiveness. Simply put, poor information management leads to unproductive actions; and poor availability of management tools has some impact to the quality of workflow outputs, such as tasks and document utilization. Stripping back the bulk of information, the workflow is addressing and providing visual aids to support understanding of what actually has yielded a greater integration of workflow methods. However, this developed understanding is not without significant performance issues impacting the effectiveness as a workflow.

5.3.1 Scope reduction

There are two reasons for reducing the scale and scope; first, the intent is to focus less on the scale and more on complexity of design with the robot; the second is that a team member left partway through this phase. At this stage of development, the workflow does not get used in multiple iterative passes. The process is still direct, following steps to an output with little feedback and generally very few, or no iterations. The design ideas are sometimes revisited, however, the major issue is productivity. Work is not completed as intended with the project rapidly falling behind the pace. The tools implemented to help manage the flow of information in the early stages include lists and milestone setting of which apparently are agreed on. Despite goals being defined and initial scope of work targeted, the process lags. In addition, intended repetition is not achieved no matter what techniques and discussions are attempted. Subsequently, at this stage after one member had left, the three remaining members gathered ideas on how the team actually works.



Design scope and management of base parameters is an independent bubble from the development of joinery systems. Ultimately, all information is joined and combined further down the workflow process as suggested, however, there is no strong integration of ideas between the two design streams. There are benefits to this in that each designer is responsible for their own research input but veers away from the intent to facilitate productive collaboration. An interesting point to add to this, is despite the fact that the two remaining designers are working independently, it is very clear from observation that there in fact is a degree of collaboration of ideas. This collaboration is actually facilitated by the social environment in which the research is conducted. Subsequently, the actual documentation and tracking of when and how collaboration is facilitated has become irrelevant. Perhaps a more logical limitation of this collaborative student environment is that iterations are not full cycles of the process. Restricted by time and working in this informal way influencing each other's decisions, explains why projects always lean towards a final designed output over repeating an iterative process.

5.3.2 Impact of Tool Design and Fabrication

New tools are required as part of experimenting and pushing the material properties further. New tools required impact directly on time spent actually designing and testing with the robot. This in turn limits the ability to run through the workflow. The Digital Fabrication workflow has not considered the impact nor the provision to design tools within its process. After all, it is counterproductive to spend a significant amount of time designing iterations of a tool. Regardless, there is a significant amount of man hours and design required to create the specific tools needed to operate the robot is desired ways. More focus on the control of robot, including safety parameters built into the simulation suite came along with the requirement for new tools. The collaborative environment facilitated by the workflow, despite the indirect nature of some interactions have led to team work on solving tooling issues. Making better design decisions is a key indicator of quality in the workflow, therefore the fact that people with different interests in the project solve the same issues together is testament to how digital fabrication facilitates a superior quality method than other like processes. The focus is directed away from targeting efficiency and instead focuses on facilitating good design.

5.3.3 Critical Performance Evaluation

The second development of a digital fabrication workflow is not an example of an efficient process, nor is it an example of good productivity and quality. There are significant productivity and quality inconsistencies which negatively impact on the effectiveness of the workflow. The flow of information is not clear as evident by design ideas not reflected on through lessons and multiple passes of the process. The strengths in this workflow are that there is a greater team understanding to the purpose of the tools, however through providing streamlined tools for uses, such as the flow chart, the usefulness is actually diminished. Key information such as requirements of each step are lost resulting in similar performance issues as the original workflow. A lack of direction early on in design development suggests a large interruption with the flow of information. Essentially, people are not able to make quick informed design decisions as a result. Subsequently, the workflow suffers from a poor workflow quality and productivity.

5.4 Developments beyond Observations, The final Workflow Discussion

An effective workflow must demonstrate strong performance in Efficiency, Productivity and Quality. These three KPI's underpin all tools, techniques and processes integrated into the development and everyday use of the workflow. For future developments of Digital Fabrication workflows, establishing a clear protocol for project initiation and facilitating the other core tools through the early project phases is a must. Early project stages are at the highest risk for both quality and productivity to be negatively affected and in turn have the largest impact on efficient performance.

5.4.1 A Protocol

A protocol document is the most important recommended tool to be implemented in future development of digital fabrication. The issue with integrating a protocol into this specific situation is the track record held by Think Machine for not fully utilizing additional documents suggested as management tools to help organise the process. A protocol document can be utilized to give specific instructions and rules for all project tools. For example; Lists categorising base parameters and design ideas are used widely in Think Machines Digital Fabrication process. The protocol would set out a uniform template and process for creating and documenting these lists. Looking back to issues under the second phase in this research, a large amount of time is wasted setting up base parameters and suggesting ideas. This bled onto later processes and effectively slowed the entire three week cycle. A protocol, to manage future developments of Digital Fabrication workflows, establishing project initiation and facilitating the other core tools is crucial to reducing the impact of this phenomenon. Moreover, the protocol can be used to define the workflow in greater detail with team. As a protocol is generally a larger document with very detailed explanations, simply adopting the methods as intended for BIM projects, the Digital Fabrication Protocol must account for the end user, a designer. As such, applying flowchart style graphics and other similar tools such as role diagrams to indicate what is required and when could be very useful. This research clearly establishes that for Think Machine, in an educational social environment, word based documents and spreadsheets are not effective tools to display this information whereas flow charts have been invaluable. The holistic approach to developing a workflow that anyone can pick up and understand applies to a protocol also.

6.0 Conclusions

6.1 Digital Fabrication Workflow performance

Efficiency is tied directly into the discussion on productivity and quality. The effectiveness and efficiency of digital fabrication workflows cannot be discussed without analysing tools and processes which facilitate better design decisions. Efficiency, Productivity and Quality are all aspects tied into the performance of digital fabrication. This thesis discusses how it is possible to qualitatively analyse performance of a workflow against these three KPI's and indicates the role project management has in positively improving team focused contemporary design. The basic workflow for a digital fabrication process has been established with development of this base in response to key issues identified in cross examination of its effectiveness. Without effective performance in all three KPI's, a workflow will have issues as is displayed in all the tested workflows. Good workflow management should lead to higher degrees of efficiency and productivity with the clear establishment of processes directly correlating with higher quality workflows. However, this in reality can be challenging to attain with social conditions and external factors having significant impacts on the performance of a workflow.

Observations of confusion, lack of motivation and deference from suggested processes have suggested poor performance in terms of efficiency at most development phases for this thesis. Ultimately, understanding the function that project management has for workflow establishment and control is the base for discussing the effectiveness of a Digital Fabrication process. The process of assessment for workflow performance has advised the need to early establishment of strong process protocols. Without early intervention in this design process, people become stuck in loops of experimenting with ideas and subsequently produce unfocused design outputs.

Think Machines research process has moved from exploratory learning of what a digital fabrication workflow could be, into detailed analysis of management techniques intergraded into the process. Drawing from similar processes such as Building Information Modelling, tools and strategies applied show mixed success in fostering effective workflow performance management. Iterative design is a key idea pushed with a Digital Fabrication workflow, drawing heavily from existing fabrication processes.

6.2 The role of Project Management

Project management has a unique position in team based design projects, able to observe and integrate ideas to better focus and foster good design. A key point this thesis addresses is that this workflow prototype does not replace any existing methods, but offers alternative methods with contemporary tools. In addition, a gap in industry expertise and performance can be identified. Contemporary fabrication processes offer the platform required to increase process efficiency resolving the underlying performance issues of the construction sector. There is a strong synergy between this idea of offering contemporary methods and improving production efficiency of the construction sector.

This research has highlighted that there is opportunity for project management tools to be utilized in contemporary process management to improve performance of workflows. A part of this research identifies significant issues with the performance of the suggested workflows and has provided a framework of tools and points to address with further study. The reality of how people interact in the social constraints of academic institutions impacts how the digital fabrication workflow has been developed and analysed. Within practice, more emphasis can be put onto inputs and outputs of processes. Furthermore, time is a significant factor for evaluating effectiveness of workflow processes however, is simply irrelevant in this research. That is not to say, observations regarding missing established milestones are not important. However, the ability to define digital fabrication effectiveness based from time analysis is not addressed.

6.3 Final Statement

Finally, workflow performance must, and can only be evaluated on the successfulness of workflow execution. This thesis has demonstrated that there are a variety of tools and management techniques that provide varying degrees of success in fostering good workflow performance. Subsequently, it is clear that a project managers role is best suited to applying and managing the integration of these techniques.

6.4 Gap in Knowledge

The main knowledge gap targeted is how the performance of the process should be assessed. The similarities between existing processes and digital fabrication suggests a start point to testing and developing management tools. A crucial part of this discussion is the limitations in which performance assessment can be applied such as the inability to objectively state what is the best workflow. The work study method is useful in developing and analysing processes as they happen, after all it is designed as a management tool to assess live processes. Future analysis of digital fabrication as a workflow, and for assessment of workflows in general, needs a quantifiable scoring method. In hindsight, the ability to breakdown and assess workflow quality, productivity and efficiency based on a scoring matrix would be an invaluable management tool.

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8.0 Appendices

8.1 Appendix One, Datasheets

Simple	Base Shape	Description of Form	Pass/Fail	Material	Depth	Inrement	Speed	Angle	Notes
	Circle								
	001	Truncated Cone, Circle to cricle	pass	0.9	80mm	3mm			Quick run, first run, great success
	019	Truncated Cone, Circle to cricle	Pass	1.2	60mm	1mm	120	30	
	020	Truncated Cone, Circle to cricle	Pass	1.2	60mm	1mm	120	45	
	021	Truncated Cone, Circle to cricle	Pass	1.2	60mm	1mm	120	60	Still getting vibration with slow speed
	022	Truncated Cone, Circle to cricle	Pass	1.2	60mm	1mm	120	70	
	023	Truncated Cone, Circle to cricle	Fail	1.2	60mm	1mm	120	80	Program was initially run without bolts. Identified material juddering indescrepency as due to the bolt holes not speed
	Dome								
	015		Pass		100	1mm	240		
	017		fail	1.2	120	exponential			too many points due to even spacing. did not quite finish
	Bowl								
	010		Fail		120	1mm	200		Stopped simulation to brace table . Bowl broke after 10seconds of restart
	011		Pass		120	1mm	200		
	012		Pass		120	0.5mm	200		
	013		Pass		120	4mm	200		Step lengths are extremely visible
	014		Fail		120	1mm	200		No cutting fluid
	Triangle								
	Square								
	005	Square to square - BASE CASE extrusion test 320mm square	pass	0.9	120mm	2mm			
	006	Square to Square - depth increased by 40	pass	0.9	160mm	2mm			
	007	Sqaure to Square - depth increased by 60	pass	0.9	180mm	2mm			
	008	Square to Square - depth increased by 80	pass	0.9	200mm	2mm			No breaking point found for entire square. Seems that angle is prime factor to consider

Comple	BASE	Description of Form	Pass/Fail	Material	Depth	Inrement	Speed		Notes
	Wobble								
	009	blob	fail	0.9	?	?			jumping to unknowns caused fail.. Steep on one face nearly vertical cause tear
	Triangle								
	001b	Triangle base shape transform to circle	pass	1.2	35mm	1mm			
	006b	Triangle base shape transform to circle	pass	1.2	80mm	1mm			
	007b	Triangle base shape transform to circle	pass	1.2	various	1mm			Three separate extrusions on one panel. No breaks or tears on steep angles. Tool paths on 2nd and third extrusion are not in contact completely at beginning of run from deformation
	Square								
	002	square base to circle	pass	0.9	120	1mm			More deformation without corner bolts. 1mm very smooth finish
	008b	Square base to triangle to circle to hexagon	fail	0.9	130	1mm			
	Hexagon								
	016	hexagon	Pass						
	018	hexagon	fail	1.2	?				hexagon waves
	002b	Hexagon with rotation 60 degrees	fail	1.2	35mm	1mm			Rotation angle to great causing undercut on face tearing the metal
	003b	Hexagon with rotation 6 degrees	pass	1.2	35mm	0.5mm			reduced chance for undercutting
	004b	Hexagon with rotation 6 degrees	pass	1.2	80mm	0.5mm			progression in depth from 003b
	005b	Hexagon with rotation 6 degrees	pass	1.2	120	1mm			progression in depth from 004b with increased increment. Could add aditional degrees rotation with more depth?
	Voronoi								
	003	5 vorinoi shapes	fail	0.9	?	2mm			Need to double check parameters before publishing export. Increment was -12mm below surface
	004	5 vorinoi shapes identical to 003	pass	0.9	?	0.2 - 0.8			had to change increment step half way through due to time constraints. Need to add aditional point in corners to keep accuracy.
	Patterned grids								
	001-6a	3x3 Hexagon Grid	Pass						Testing repeatability, how unstable/variable is the current jig

8.2 Appendix Two, Lists

Example of tracking list used by Think Machine to organise and categorise what test have been completed

	Description	Hard	#	Form	pass/fail	Testing	Notes
Phase one	Basic Parameter	x	001	Cone	P	Form	
		x	002	sq - circle	P	Form	
		x	003	Voronoi	F	Form	Fail due to - Error i
		x	004	Voronoi	P	Form	
		x	005	Square	P	Depth	
		x	006	Square	P	Depth	
		x	007	Square	P	Depth	
		x	008	Square	P	Depth	
		x	009	Wobble	F	yolo trial	Fail due to - loft tc
		x	010	Bowl	F	Increment	Fail due to - table
		x	011	Bowl	P	Increment	
		x	012	Bowl	P	Increment	
		x	013	Bowl	P	Increment	
		x	014	Bowl	F	Increment	Fail due to - No cu
		x	015	Dome	P	Form	
		x	016	Hexagon	P	Form	
		x	017	Dome	P	Increment	
		x	018	Hexagon	F	Depth	
			019	Cone	P	Angle	
			020	Cone	P	Angle	
			021	Cone	P	Angle	
			022	Cone	P	Angle	
			023	Cone	F	Angle	not enough data t
			024				
Phase Two	Reliability of se	x	001a-004a	3x3 Hex Grid	P	Repeatability	To ensure the jig r
a.k.a. muffin tins		x	005a-006a	3x3 Hex Grid	P	Repeatability	
Phase Three	Complex shapes	x	001b	triangle to circle		?	
		x	002b	hexagon		?	
		x	003b	hexagon		?	
		x	004b	hexagon		?	
		x	005b	hexagon		?	
		x	006b	triangle to circle		?	
		x	007b	triangle to circle		?	
		x	008b	square - tri - c- h		yolo trial	

8.3 Appendix Three, Possible Variables

Example of spread sheet created to help identify future experiment ideas

	Variables		Examples of variables						Controlled through	Program
Form	Tool path type		Stepped contours						Digital	Grasshopper
	Increment Step (mm)			0.6	1	2	3		Digital	Grasshopper
	Total Depth (mm)			80	120				Digital	Grasshopper
Robotic translation	Angle of plane for targets on toolpath			XY surface	Normal to the Polysurface				Digital	Grasshopper
How the robot interprets the creati	Speed (mm/s)			120					Digital	Grasshopper
	Movement type		Linear Interpolation						Digital	Grasshopper
	Number of points		determines resolution or path quality						Digital	Grasshopper
Material Properties	Tool head material		Hardened Steel	aluminium	ABS plastic				Physical selection	
	Grade of Material (material dependant)								Physical selection	
	Material thickness			0.9	1.2				Physical selection	
	Supporting frame bolts (number)		Corners	Half	Full				Physical selection	
	Surface treatment			oil	no oil				Physical selection	

8.4 Appendix Four, Budget tracking

BUDGET SUMMARY

LIST OF EXPENSES

PROJECT FUNDS ALLOTTED	Anticipated Cost	FUNDS REMAINING
$3,000.00	**$3,099.90**	**($99.90)**

#	Item	Category	Rate	#	Amount
1	Steel rod 60mm	Steel	25.5	1	$25.50
2	???????	?	480.28	1	$480.28
3	Aluminium	Aluminium	289.8	1	$289.80
4	600x600 coated / 600x200 coate	Materials	32.5	1	$32.50
5	Black Card	Materials	9.8	2	$19.60
6	Ply	Materials	140.3	1	$140.30
7	Clamps	Tools	107.75	1	$107.75
8	Aluminium	Aluminium	220.75	1	$220.75
9	Foam Board	Materials	12.1	1	$12.10
10	?	Materials	9.1	1	$9.10
11	Aluminium	Aluminium	480.02	1	$480.02
12	ABS White	Materials	50	1	$50.00
13	Steel Rod 1x38mm	Steel	8.8	1	$8.80
14	ABS filament roll	Materials	30	1	$30.00
15	Ply	Materials	204.89	1	$204.89
16	Steel Rod	Steel	95	1	$95.00
17	BOLTS	Materials	410	1	$410.00
18	Aluminium	Materials	483.51	1	$483.51
19	John Charges..	?	0	1	$0.00
	Total				$3,099.90

BUDGET SUMMARY

LIST OF EXPENSES

PROJECT FUNDS ALLOTTED
$3,000.00

Anticipated Cost
$2,986.30

FUNDS REMAINING
$13.70

Item	Category	Rate	#	Amount
Aluminium - *1.2mmx2400x1200*	Materials	73.48	14	$1,028.72
Timber - Ply *18mmx2400x1200*	Materials	61.55	12	$738.60
Steel	Materials	79.49	2	$158.98
Glue	Materials	50	1	$50.00
Additive Printing Materials	Materials	60	1	$60.00
Misc fixings *(Bolts, Nails)*	Materials	250	1	$250.00
Router Time *(per/hr)*	External Contractors	50	6	$300.00
Welding Time *(per/hr)*	External Contractors	40	4	$160.00
Lazer Cutting *(per/hr)*	External Contractors	40	6	$240.00
Total				$2,986.30

Budget lists and spreadsheets where in valuable in organising funding whilst managing expenditure on test materials.

8.5 Appendix Five, Lessons Learnt

This is a live tracked document where all key observations and lessons for process development from the wider team are stored. This document went through various form and eventually was replaced with iterative design loops and personal reporting. The document was kept to provide legacy lessons to recall at later dates.

Forming

- *Depth not concern (for current project) – reassess for new jig?*
  - *Double curve will probably have stretch effect?*
- *Multiple forms will alter the face deformation so second*
  - *+forms will not be extruded on flat surface?*
- *More deformation without corner bolts*
- *Fine increment = smooth finish*
- *Beware of undercutting*
  - *(due to rotated shapes)*
  - *Will stretch the form and tear the sheet*
- *Need additional targets in corners of forms*
- *Double check the parameters before exporting the code*
  - *Workflow simulation step (not always used?)*
- *Shorter toolpaths need less points as maths becomes too hard for the robot with lots of points all together*

To do's from these

- *Zones have not been investigated*
  - *Are they of any use? Out of scope?*
- *Organised system of programs with good descriptions*
  - *Database….*

Jig & construction

- *Time is too long is general opinion after building*
  - *Find ways to be more productive when down fabricating*
- *Safety planes are important to ensure no damage when fabricating*

Tatu

- *Manual drilling of additional connections caused curling issue*
  - *Robot to drill these in future*
- *Lack of iterative design intended from the start of the project.*
  - *Workflow issue and design issue.*
- *Lack of all parameters fully influencing the design*

To do's from these

- *Wooden support needed*
  - *Must become a parameter from which the design responds*
  - *The wood structure itself needs parameters*
- *What is the function of the pavilion?*

- *Sunlight, wind, shade*
- *Need to capitalize on these parameters*

Workflow

- *Overall, Documentation not followed*
- *For NEW jig, MUST watch and somehow document that the Simulation run does not cause robot to hit the jig/walls etc.*
    - *Safety planes*
- *Great goal, doesn't reflect the reality of how people constructed final design outputs.*
- *Focus on design first then constructed final with little iterative design input. (maybe result of construction time pressures, understanding of process)*
- *Database idea not fully utilized. Seems more useful for future runs through process. Database needs significant work to be utilized as intended (current existence as file system alone does not work.*
    - *Needs to be true data base. (additional maintenance and governance). Initial database from project start had flaws also as additional effort seemed to reduce archies willingness to use the system fully (understanding of use / importance?)*
- *Did not begin in reality with a 'LIST of ideas', design team came up with design which was then the focus point.*
- *Lessons learnt not utilized although NEED to be to make this iterative process.*
    - *Document never clearly established. Team never really reached the point where it could be made.*