# Integrating Agile within Complex Hardware Development via Additive Manufacturing

by

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Submitted to the Sloan School of Management, Department of Mechanical Engineering

in partial fulfillment of the requirements for the degrees of

Master of Business Administration

and

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2020

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## Abstract

A major benefit of Additive Manufacturing (AM) is a faster timeline from design to fabrication. As AM has matured to be able to create functional prototypes and end-use products, the ability to quickly fabricate physical hardware iterations without associated tooling costs and lead times is now possible.

Software companies have embraced iterative-based product development processes (PDP) such as Agile. Iterative development has allowed for the validation of innovative and untried solutions, fueling the rapid speed of software development. However, within complex hardware industries, like automotive and aerospace, almost all companies instead follow a Waterfall or Phase-Gate PDP. Large capital costs, along with the aforementioned lengthy tooling and supplier lead times, make the control and predictability of a Phase-Gate process appealing. However, the trade-off is a process where the final content gets decided near the beginning of a multi-year timeline, often translating to product launches with soon-to-be stale technologies.

Within the context of automotive, this thesis explores how leading edge technology could continue development in a parallel Agile process. Though the use of AM, the new technology could be integrated later into a Phase-Gate process with minimal schedule risk or cost. This process keeps the strict one-way review gates for the more stable components, while allowing greater flexibility for innovative features that could benefit from further iteration. I use Design Structure Matrix theory to simulate the performance and schedule of this proposed PDP. I then discuss the implications of this new PDP architecture and its benefits for complex hardware industries in general.

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# Acknowledgments

I would like to thank my internship supervisor, John Zinser. He gave me the freedom and required accesses while on internship to explore my academic interest and passion around hardware development. Anytime I had a question, he always temporarily dropped what he was doing to address my inquiry. I would also like to thank Ali Shabbir, a previous MIT Course 2 alum at General Motors, who always gave me great mentorship, as well as took the time to introduce me to contacts within the company who ended up being of great assistance. Another mentor I would like to thank is LGO '96 alum, Todd Huston, who acted as a champion for the LGO/GM relationship and would take weekly calls with me just to see how the internship was going. Additionally, just a big thank you to the General Motors Additive Design and Manufacturing team, including Kevin Quinn, Donald Vanderlugt, Zach Steffes, Brennon White, Marcus Baker, Paul Wolcott, and Andrew Cunningham. You were all very generous with your time and made the whole experience a pleasure. I hope some of what I wrote here is at all useful to advancing your team's objectives.

I of course must thank my two advisors, Professors Stephen Graves and John Hart. Both of you were very responsive and gave critical feedback to this project. Thank you Professor Hart for also folding me into your Mechanosynthesis Lab. That provided a great peer group for me to bounce ideas off of. That group also humbled me when I saw the cutting-edge research they were doing within the Additive Manufacturing space.

Big thank you to my LGO Class of 2020 peers. I could not have wished for a more exemplary group of classmates, both professionally and personally. The dual degree program was hard, but a lot of fun. And I survived and thrived in it because of you all. I cannot be but a little sad that our time together was cut a bit short by the COVID-19 crisis. However, it was an amazing experience, and I have no doubt that we will stay close as an LGO '20 family for decades to come. To future LGO's, do not lose sight that the relationships you build among each other and the resulting connection to years past and prior are probably the greatest asset of this program.

Also, sorry that my internship and following thesis were not good enough to save the LGO/GM relationship!

Finally, I end by thanking my mother Luz and my partner Kelly. My mother has always had a blind faith in me which is very nice and motivating. Kelly's faith was slightly less blind, but that ultimately made it very constructive. When I needed honest feedback, Kelly was there. When I needed someone to just listen, Kelly was there.

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# Chapter 1

# Introduction

Additive manufacturing (AM), or 3D printing, refers to manufacturing processes and technologies that fabricate parts, directly from 3D digital files, through the successive addition of layers of material. One of AM's major benefits is a faster timeline from design to fabrication without the need for part-specific tooling. As AM matures to be able to create functional prototypes as well as end-use products, the ability to more quickly iterate physical products without associated tooling costs and lead-times becomes possible. In this thesis, I analyze how this technology could enable Agile development within the product development processes (PDP) of complex hardware that includes long lead time components.

## 1.1 Project Motivation

The economic growth of the first half of the 20th century was dominated by the Second Industrial Revolution, bringing about the ability to mechanically mass produce physical goods. During the latter half of the century, economic globalization took hold and production lines and manufacturing processes were perfected. Manufacturing capacity then became a commodity that was easily off-shored. Since then, growth in the economically developed world has been spurred mostly by the Information Revolution. Common practices within software development, to include Minimum Viable Products and Agile Development, revolve around rapidly developed and deployed products that receive feedback or input into future product development iterations. Companies that manufacture complex hardware, such as an automobile, have not been able to take full advantage of rapid iterative development due to the high capital costs associated with tooling and setting up an efficient production line.

Iterations within the early design phase and assembly matching process (the part of manufacturing engineering where component interfaces are refined) are still required. However, for complex products, physical iterations are often slow and expensive and cause high product development costs. So even when further iterative design would bring benefit to a product, most companies make the financial decision to forgo such efforts. Instead, industries such as automotive and aviation rely heavily on repeated or slightly tweaked base architectures to reign in costs and risk. Ultimately, that leads to years of evolutionary product offerings rather than revolutionary innovations.

In essence, the high capital costs of physical iterations hinders the speed of innovation within complex hardware industries. By eliminating certain tooling costs, AM can lower that cost and increase the speed of iterative, agile hardware development. Through this thesis, I aim to show how AM can accomplish that, while still respecting some of the constraints inherent to these types of industries, e.g. multi-year development time-frames and long lead times for many of the product's larger components.

## 1.2 Problem Statement

Visions of the future have often revolved around physical technologies. From flying cars to hover boards to personal robots, the previous generation's ideations of the future seem to not have materialized as thought. While technologies that revolve around complex hardware have not evolved as quickly as imagined, software technology evolution has surpassed many expectations. A key reason behind this is the speed of product development which is enabled by the quickness and cheapness of iteration. This type of iteration is at the core of product development processes such as Agile and DevOps.

In contrast, complex hardware has mainly been developed using the same Phase-Gate or Waterfall processes that have been used for the last half century (Tatikonda and Rosenthal, 2000, p. 405). This type of product development process is based on breaking up the process into a series of phases and having structured review gates at the end of those phases. Once a project passes through a gate, the idea is not to return to previous phases. This process helps break up a complex project into manageable pieces, gives management set opportunities at the gates to review and exercise control of the project, and theoretically saves a project from extensive rework by freezing decisions at those gates. However, all this control often comes at the cost of flexibility and thus the ability for projects to react to new data.

Additive manufacturing holds the promise to change that rigidity for complex hardware development through making iterations cheaper and quicker. Predictably, there has been recent industry and academic interest in how you could apply Agile development concepts to hardware and systems engineering. If the hardware is too complex or expensive to build minimum viable products and so preventing a truly Agile process, could you use some type of integrated or parallel Agile-Phase Gate method?

This thesis aims to answer the following question:

1. While 3D printing the whole product is currently impossible nor desirable for most complex hardware, how do you identify which components are ideal to utilize AM for from a process perspective?

2. With those parts identified and within the constraints of a phase-gate process, how can AM be used to economically execute Agile hardware development?

3. How can you then redesign the overall product development process to enable an integrated Agile-Phase-Gate process that keeps the desired controls of a Phase-Gate process when you need them, but also makes the process more capable of reacting to new information?

## 1.3 Statement of Hypothesis

The hypothesis of this project is that the long lead times and expenses of tooling have prevented complex hardware manufactures from implementing Agile or iterative-based product design processes. While additive manufacturing is unable to manufacture the entire product, its use for certain components that are in need of further development or susceptible to many or expensive changes during physical validation will provide immense value to companies. As additive manufacturing has evolved to be capable of building end-use components, the ability to redesign the product development process around a Parallel Agile-Phase Gate system becomes possible.

One of the greater benefits of a Parallel Agile-Phase Gate PDP is that innovative features can be developed in parallel via an AM-enabled Agile process while the rest of the product can continue to use the more traditional Phase-Gate PDP. This allows technologies that are not quite ready at the beginning of a multi-year development process to become ready and be easily integrated into the product closer to launch. This means that the technology included in the launch is years more current than if the product had been developed with a more traditional Phase-Gate PDP that had required content decisions to be made years before launch.

Creating such a new product development process that is able to integrate both Agile processes when needed and maintain the control and structure of a Phase-Gate process would enable more innovation within complex hardware development without adding substantially increased monetary and schedule risks.

## 1.4 Project Approach

The first phase of the project involved extensive interviewing and then analysis of an automaker's current product development process. While in many ways, it resembled a standard Phase-Gate process, there were extensive digital iterations within the early engineering design process that were accomplished through Computer Aided Engineering (CAE) and virtualization technologies. However, physical iterations were limited to very early advanced concept designs and then again at the very end during final vehicle validation.

Using a Design Structure Matrix (DSM), I constructed a simplified version of a similar product development process. This model was based on a previous thesis (Sequeira, 1991) within the car industry combined with extensive documentation of an automaker's vehicle development process obtained while on internship with that automaker. This process was generalized in order to protect proprietary information.

Focusing on the use-case of late stage technology integration, I propose a new Parallel Agile-Phase Gate Product Development Process. I then analyze that new process through DSM simulation, and present the timing and theoretical performance benefits of this process.

## 1.5 Thesis Structure

The thesis is organized as follows:

**Chapter 2 - Background** presents an overview of the current state of auto manufacturing product development to include the Phase-Gate process and the use of prototype and production tooling for physical builds. On overview of Agile development is provided. Also presented is the current state and trends within the additive manufacturing sector and how automotive is incorporating the technology.

**Chapter 3 - Literature Review** goes over the academic articles that discuss the applications of additive manufacturing with a focus on functional prototyping. It also presents articles that pertain to product development theory including Design Structure Matrixes (DSM) and other proposed Agile-influenced hardware product development processes.

**Chapter 4 - Analysis of Planned and Unplanned Iterations within a Product Development Processes** presents a taxonomy on how to categorize iterations within a product development process with the goal to later show how AM can help encourage positive iterations and limit the cost of certain undesirable, but inevitable iterations within a PDP.

**Chapter 5 - Modelling and Simulating a Product Development Process with Design Structure Matrices** presents the mechanics of a DSM and how it is used to model the information flows and execution of a product development process.

**Chapter 6 - Analysis of a Phase-Gate Product Development Process** presents a general description of a representative vehicle product development process. A generalized Design Structure Matrix with process dependencies is introduced and explained.

**Chapter 7 - Presenting a Parallel Agile-Phase Gate Process** introduces a new PDP that uses AM to create an Agile hardware development process that runs parallel to the main Phase-Gate process. The simulated schedule of this process is presented and used to show how the new process compares to the current process, as well as to another proposed Hybrid Agile-Phase Gate Process. A financial framework is also introduced that could be used by companies to help them decide on the value of pursuing specific development efforts via this Parallel Agile process.

**Chapter 8 - Conclusions and Future Work** extrapolates the learnings from the automotive industry to other complex hardware industries. The greater impact of AM on physical innovation is discussed. The chapter wraps up the project with a discussion on future academic studies that would be needed to validate some of the theories presented, as well as discusses further steps hardware companies could make to fully take advantage of AM within their development process.

# Chapter 2

# Background on Current State

The following chapter gives background on automotive manufacturing, automotive product development, the Agile methodology, and additive manufacturing. It presents a general description of the current state of each of those topics to set the stage for how integrating an Agile PDP through the use of additive manufacturing can improve the product development process within a complex hardware industry, such as automotive.

## 2.1 Automotive Manufacturing

Defining the Industrial Revolution as having four stages (see Figure 2-1), the first was the use of water and steam powered machinery in the late 18th century. The second was the introduction of production lines and the division of labor at the start of the last century. The third was the use of electronics and robots to automate manufacturing. And finally, Industry 4.0 (a subset of the still to be defined 4th Industrial Revolution) is the current introduction of cyber-physical systems into the factory.

Based on those definitions, the automotive industry had in many ways led the way for the 2nd and 3rd Industrial Revolutions. While not the first assembly line, Ford and the Model T is one of the most famous early examples and was possibly the first moving line (Ford and Crowther, 1922). The invention of the six axis robot,

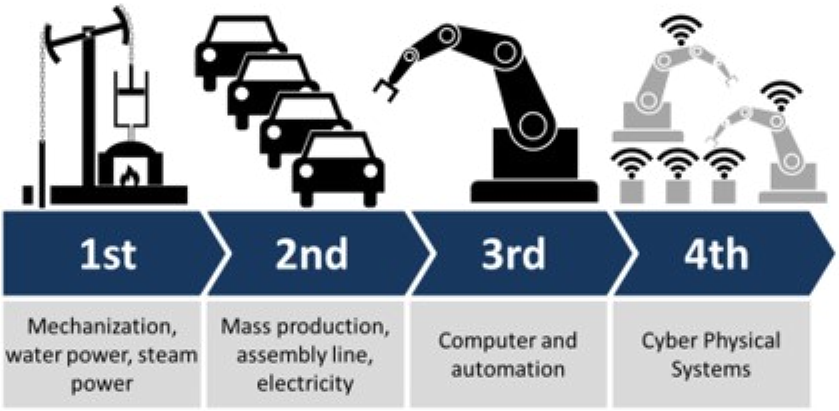

1st
2nd
3rd
4th
Mechanization, water power, steam power
Mass production, assembly line, electricity
Computer and automation
Cyber Physical Systems

Figure 2-1: Industrial Revolutions
Source: Christoph Roser at AllAboutLean.com

or Stanford Arm, and its use in the automotive industry in the 1970s was arguably the start of the third revolution. The auto industry is still by far the largest user of robotics, accounting for 38 percent of industrial robot installations within the US as of 2018 (Heer, 2019). Currently, automation and robotics are heavily used for welding and painting of a vehicle. These are tasks that require repetition, precision, and can be dangerous. Movement of material throughout a factory via unmanned ground vehicles is also becoming very common. However, for the general assembly of a vehicle, a task that can have high variability due to feature options and can require more dexterity, human labor is still predominantly used.

One could not mention auto manufacturing without mentioning the Toyota Production System (TPS) and the associated Lean practices. Not popularized in manufacturing literature until the early 90s with the publication of *The Machine that Changed the World* (Womack et al., 1990), TPS had been under development in Japan decades earlier under the auspices of Eiji Toyoda and Taiichi Ohno. More of a culture centered around continuous improvement than a set of specific practices, TPS increases productivity through finding ways to continuously eliminate wasteful practices and make the manufacturing process more efficient. A core part of TPS is the concept of *jidoka*, which can be loosely translated as “automation with a human touch". This concept encourages the automation of processes but with the important feature of the machine automatically stopping when detecting an abnormality and

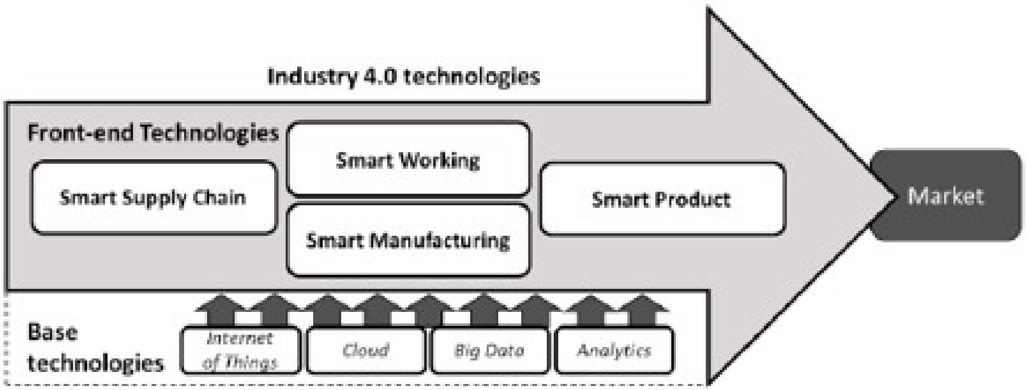


Figure 2-2: Industry 4.0 Technologies
Source: Frank et al., 2019

alerting a human to the problem in order to fix it (Earley, 2020).

The adoption of the TPS-derived Lean methodology and automation by automakers of all nationalities since the 1990s has led to large increases of productivity and production quality in the industry. According to the Bureau of Labor Statistics, auto manufacturing has grown in worker productivity by 65% from 1987 – 2018 as compared to 42% for general machinery production or only 18% for fabricated metal goods (BLS, 2019). A study by the McKinsey Global Institute attributed 45% of the productivity increase from 1987-2002 to Lean production implementation as opposed to other product factors and market externalities (Baily et al., 2005).

As mentioned earlier, Industry 4.0 (see Figure 2-2) centers around how the digital revolution of the last couple decades will translate into the factory. This concept is not well defined, but it includes such things as the smart factory, with machines and sensors that can give real-time feedback and make decisions on its own (automation without the human touch), and digital fabrication (Frank et al., 2019). Almost all industries, including automotive, have some efforts to realize that former idea of the smart factory. The smart factory promises to make current mass production lines more efficient. Less in focus, however, is how digital fabrication - the ability to reliably create a functional product by loading up a design file - can enable low-volume, agile manufacturing and how that could improve the overall product development process.

In order to make automobiles at large quantities, which can be over a million a year for more popular architectures like trucks, highly efficient production lines with sophisticated tooling must be used. For metal parts, this can be in the form of high pressure die casting or stamping. For plastics, it is high volume injection molding. The tools need to keep up with assembly takt times as low as 1 to 2 minutes for the most popular vehicles.

During the product development cycle, tooling can take the form of 'hard tooling' or 'soft tooling.' The former is for a component whose design is finalized, the latter for one that might change. 'Hard tooling' is the production tooling that can be used from thousands to millions of times. This robustness obviously does not come cheap and large stamping dies can cost in the range of a $100k dollars with months of lead time from the supplier. 'Soft tooling' or prototype tooling on the other hand can usually only last 10's of runs. But because it is made with softer materials like aluminum or other composites, it is cheaper and has a shorter supplier lead time in the weeks to month range. It can also sometimes be modified slightly for small design changes. However, soft tooling is still expensive at up to tens of thousands of dollars and the lead times are not trivial. In general, the ability to commit to hard tooling without the extra step of soft tooling is encouraged when possible.

All this leads to 'front-loading', or committing to final designs up front, being prioritized to minimize product development costs. A large proportion of the automobile's design is frozen early on, meaning learnings and improvements discovered during the product development process are conservatively applied. These freezes are accomplished through the use of strict review gates. The general Phase-Gate process that almost all vehicle development follows will be discussed in the next section.

## 2.2 Automotive Product Development

In the mid 20th century, the Space Age, and resulting Space Race between the Soviet Union and the United States, brought the rapid development of new technologies. The development of these space systems with these new technologies brought huge

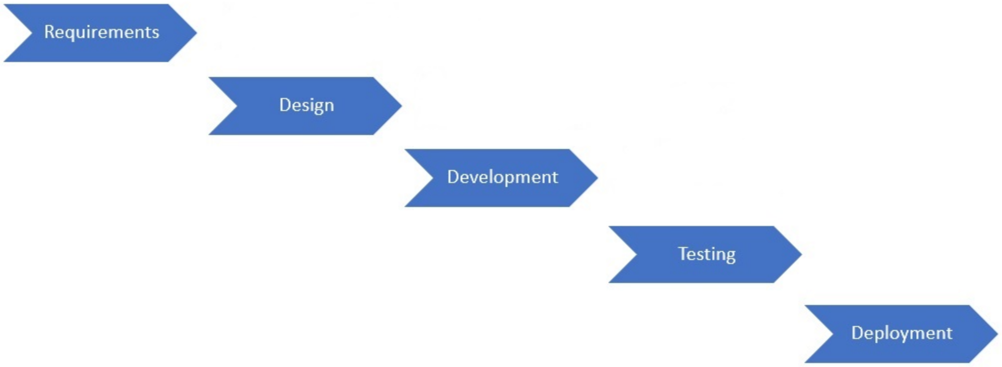


Figure 2-3: Phase Gate PDP

integration complexities. A new method of managing these complexities and risks brought NASA to develop their early Phased Review Process, a derivative of which is still used today (Blythe, 2014). The basic concept of this Phased Review Process was to set up a series of reviews where sequential milestones could be assessed before further resources were expended on the project.

This process naturally got adopted by the private sector and is now widely referred to as a Phase-Gate or Waterfall process. The popularity of this model was furthered by the work of Robert G. Cooper in the late 80s, where he described the process in his book *Winning at New Products* (Cooper, 1986). Cooper uses the term Stage-Gate to describe his process, but for the purposes of consistency within this paper, processes in this family will be referred to as Phase-Gate. This process is advantageous in that it gives management multiple opportunities for oversight at key decision points, i.e. gates. These gates are both used to find and correct issues and also to add or take away resources from projects as necessary.

But with those advantages, comes the disadvantages associated with very structured processes and oversight deliverables. Cooper acknowledged some of those limitations in an interview in 2014, "But there are still criticisms of Stage-Gate that persist, for example, it's not adaptive enough and does not encourage experimenta-

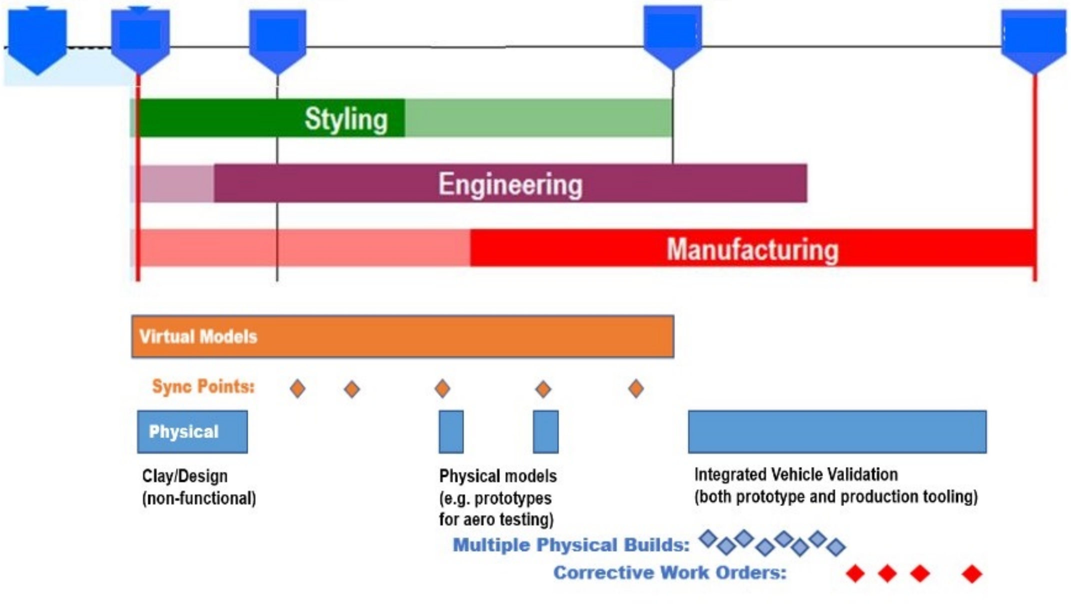


Figure 2-4: VDP with Milestones and Sync Points

tion - which means it is good for product improvement and renovation projects, but not for the real big, game-changing innovations. And for the current state-of-the-art Stage-Gate system those critics are partly right" (Cooper, 2014). However, the advantages of the oversight the gates provide to a project often outweigh the drawbacks, especially when dealing with large engineering teams and looking to incrementally improve rather than invent complex new products.

In Figure 2-4, you can find a simplified overview of an automaker's Vehicle Development Process (VDP). To appreciate the complexity and scope of the process: the true template that includes all the processes, milestones, and deliverables includes thousands of items and is too large to fit on a large desk when printed out. Also note that this particular graphic shows the design and engineering stages of the Phase-Gate process, but does not include the beginning requirements and end deployment phases. The large blue blocks on the top correspond to the key milestones or gates. While the overlap of the bars show that some parallel processes do happen in order to speed up the process, going backwards is neither desired nor encouraged.

However, when creating anything new, iterations are inevitable. The orange diamond shapes at the bottom indicate virtual sync points where teams come together to review progress and adjust work based on that review. During the Styling and early Engineering phases, advancements in the complexity and accuracy of Computer Aided Design (CAD) and Computer Aided Engineering (CAE) software technologies have enabled more digital iteration at the beginning of the process. In the physical side of the process, automotive has for a long time used clay modeling to hone their early design concepts into realizable vehicles. Automotive was also an early adopter, going back almost three decades, of using early 3D printing technologies to augment their clay designs to create those non-functional prototypes.

Once the Engineering phase is completed, the designs are then manufactured with both prototype and production tooling to test and validate the vehicles. As mentioned in the previous section, prototype or soft tooling is used to allow changes to be made based on physical learnings during testing and validation. However, these changes are often small due to the expensive nature of making changes to tooled parts that can have second and third order effects on other physical components.

The frequency and magnitude of changes made during this physical testing and validation stage are much more constrained than the early iterations during the design and digital phases. This is because changes at the later stages are much more expensive and can have serious schedule consequences.

## 2.3 Agile Product Development

This section presents a very brief overview of Agile Development. Some form of iterative product development has been around since the early beginnings of computer software development during the mid-20$^{\text{th}}$ century. As mentioned earlier in the Introduction, controlled iterations within product development are an important part of translating learnings into product improvement. In many ways, iterations within product development are an embodiment of the scientific method - systematic testing and experimentation, followed by modification of hypotheses based on the measurements of those experiments.

The formalization of the concept of the rapid, iterative product development

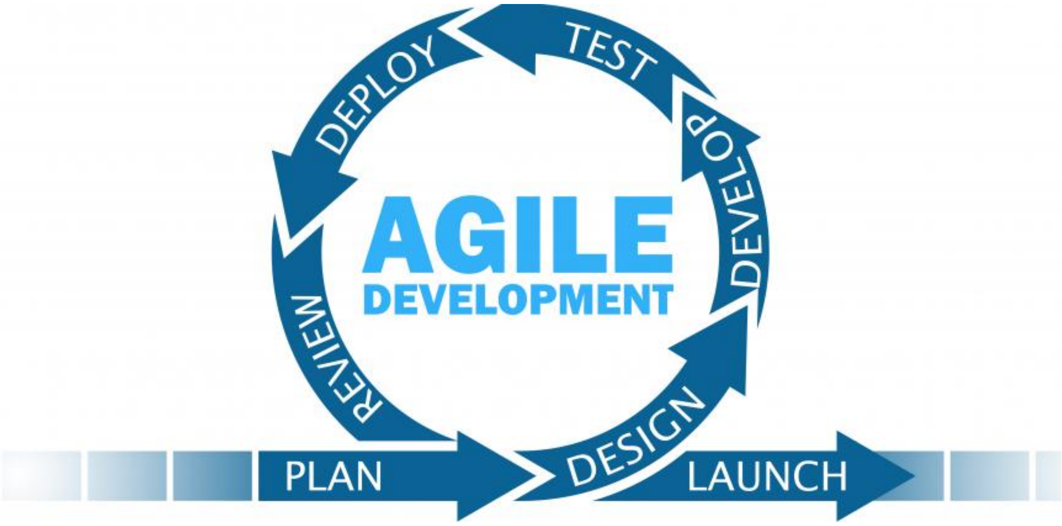


Figure 2-5: Agile Development Process
Source: www.prometsource.com/blog/create-plan-and-still-be-agile

sprints that are well known today can be traced to a group of software developers who in 2001 came together to write the *Manifesto for Agile Software Development* (Beck et al., 2001). They came up with 12 principles, with many specific to software and the ability to deploy workable pieces of software very rapdily. However a few key principles that could be applicable to large product development projects in general are:

- *Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.*

- *Business people and developers must work together daily throughout the project.*

- *Working software is the primary measure of progress.* (Can exchange the word *product* for software above.)

- *At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly.*

The concept of *Agile* is often described as more of a methodology upon which various iterative development processes have been built upon or belong to. One of the most popular is *Scrum*. The term was first introduced way back in 1986 by

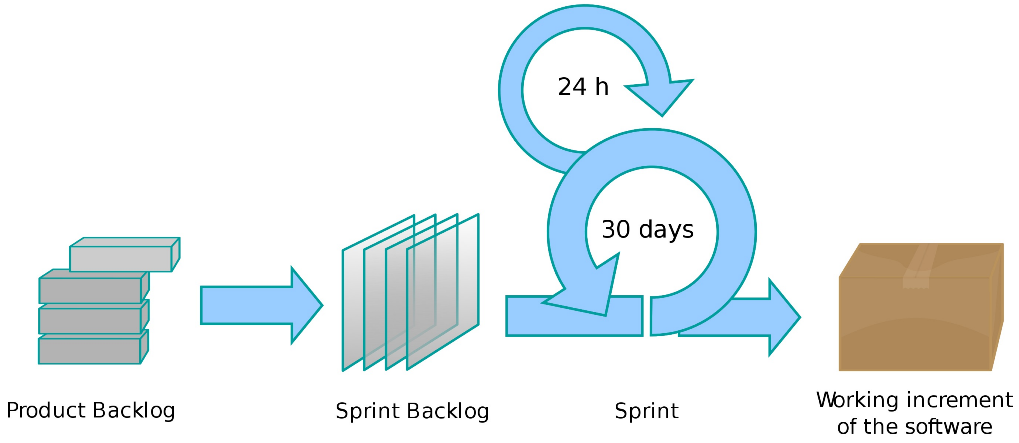


Figure 2-6: The Scrum Process
Source: Lakeworks via Wikimedia Commons

Hirotaka Takeuchi and Ikujiro Nonaka in a Harvard Business Review article entitled *The New New Product Development Game* (Takeuchi and Nonaka, 1986). Those two would later help draft the *Agile Manifesto*. The key concept of Scrum is that small teams complete iterations of the Agile Process as shown in Figure 2-5 every two to four weeks. Each of these iterations is known as a *Sprint*. They have quick daily planning meetings, led by a *Scrum Master* to make sure the team is synced and most effectively completing tasks off their *Product Backlog* to create a working, testable product at the end of the Sprint. A simple representation of this is shown in Figure 2-6.

Agile ideas have begun to influence how companies are doing hardware development. However, most of that work has focused on incorporating Agile management and culture principles into a traditional product development process rather than how an organization could feasibly create functional hardware products quickly. Section 3.2 of the Literature Review will present some of those works. Cooper, who was mentioned in the previous section, has released a couple pieces of literature on how one might implement a Hybrid Agile-Phase-Gate process (Cooper, 2016; Cooper and Sommer, 2018). However, it has drawbacks, mainly because it still keeps the Agile process within the strict gating system of a Phase-Gate process. This proposed PDP by Cooper will be discussed and compared in more detail in Section 7.5. One of the main goals of this thesis is to show how the recent improvements within Additive Manufacturing, which allow for the creation of functional prototypes, can enable a true Agile process to exist in parallel and then be seamlessly integrated with a Phase-Gate PDP.

## 2.4 Basics of Additive Manufacturing

The automotive industry has been using 3D printing technologies for decades for design mock-ups. Along with clay models and techniques that can be best described as industrial arts and crafts, 3D printing was an important tool in creating non-functional prototypes in order to make early design decisions.

What has changed within the last five years is the ability through metals and stronger polymers to make functional prototypes as well as end-use components. Companies like EOS, Renishaw, and ConceptLaser are leading the way with metal Selective Laser Melting - a process that uses a laser to melt powdered metals together, layer by layer. The classic fused deposition modeling – where melted plastic is extruded through a nozzle – has gotten more robust with new stronger polymers being created as well as innovations like MarkForged's dual material jetting that adds layers of material like Kevlar or carbon fiber to strengthen the parts.

This paper will focus more on product design processes and a business case for the use of additive manufacturing rather than the technology itself. Nevertheless, the following is a very brief overview of the more widely used additive manufacturing techniques. Most of this introductory information was derived from the book *The 3D Printing Handbook: Technologies, design and applications* published by the company *3D Hubs* (Redwood et al., 2017).

### 2.4.1 Fused Deposition Modelling (FDM)

Brief Description: A spool of material is melted and then deposited by a nozzle on a bed, building up the object. The nozzle is then raised or the bed is lowered to build

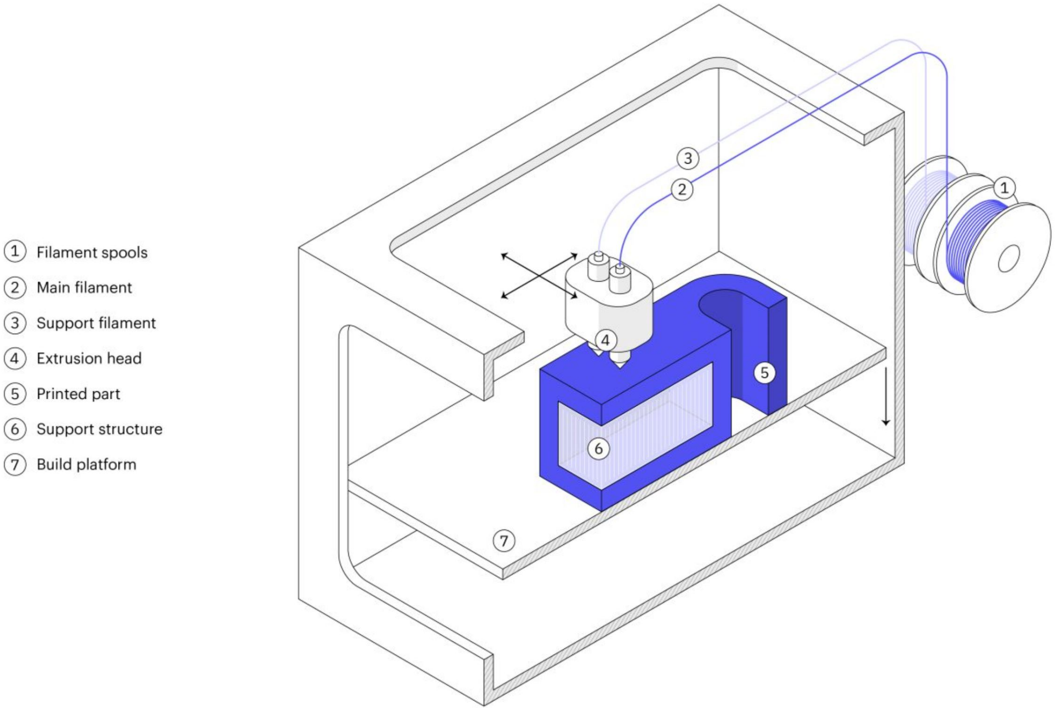


Figure 2-7: Fused Deposition Modelling
Source: www.3dhubs.com/guides/3d-printing/

successive layers. Support structures are required to hold up any overhangs. More advanced machines have additional nozzles to either lay down different materials for the same build or to deposit a soluble support material for easier post-processing.

Pros: Relatively Inexpensive; Many materials available; Can be multi-material; Soluble support materials; Ability to print large sizes.

Cons: Poorer resolution; Non-isotropic - more easily breaks along layer lines; Support material waste.

### 2.4.2 Stereolithography (SLA)

Brief Description: A bed of polymer resin is solidified using a UV light source. Support structures of the same material are also printed.

Pros: Great resolution; Isotropic properties.

Cons: Less material selection; More expensive; Single material at a time; Supports harder to remove; Strength not currently there for most functional uses.

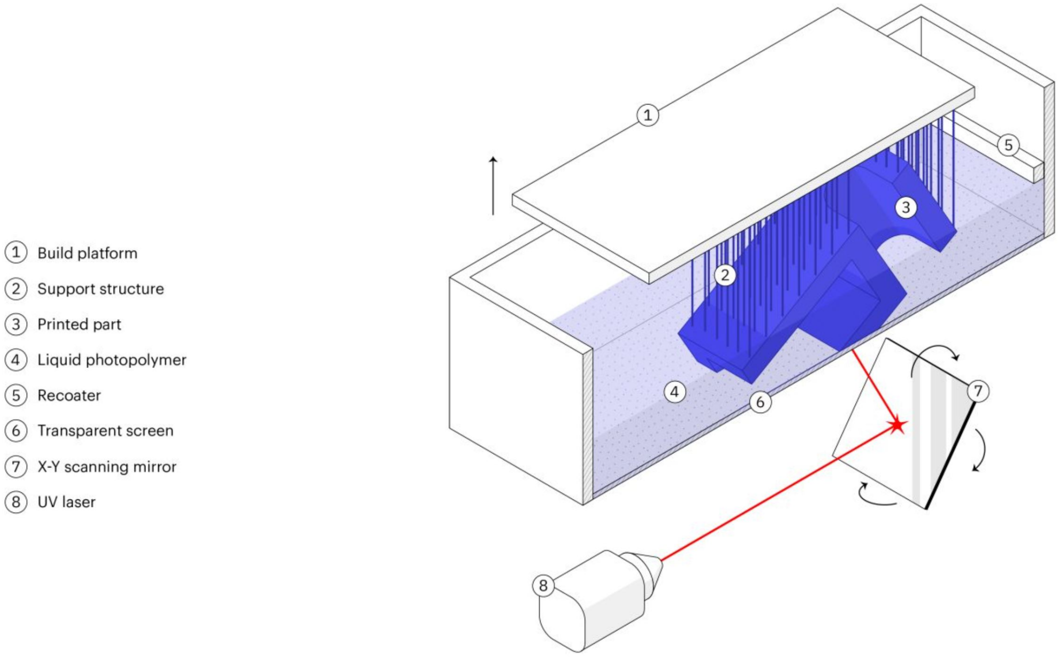


Figure 2-8: Stereolithography
Source: www.3dhubs.com/guides/3d-printing/

### 2.4.3 Selective Laser Sintering (SLS) and Melting (SLM)

Brief Description: A bed of powderized plastic (in the case of SLS) or metal (SLM) is fused together using a laser. Thin layers of fresh powder are laid down over the course of the process. Support structures are not needed due to the unused powder holding up the part.

Pros: Powder as a support; Wide variety of materials; Greatest geometric flexibility.

Cons: Proprietary powders; Single material; Restricted reusability of powder (especially with SLM). Cons: Poorer resolution; Non-isotropic - more easily breaks along layer lines; Support material waste.

### 2.4.4 Binder Jetting

Brief Description: A bed of powderized plastic or metal is selectively coated with a binding agent. Thin layers of fresh powder are laid down over the course of the process. A brittle part comes out of the bed and sintering is required to harden the

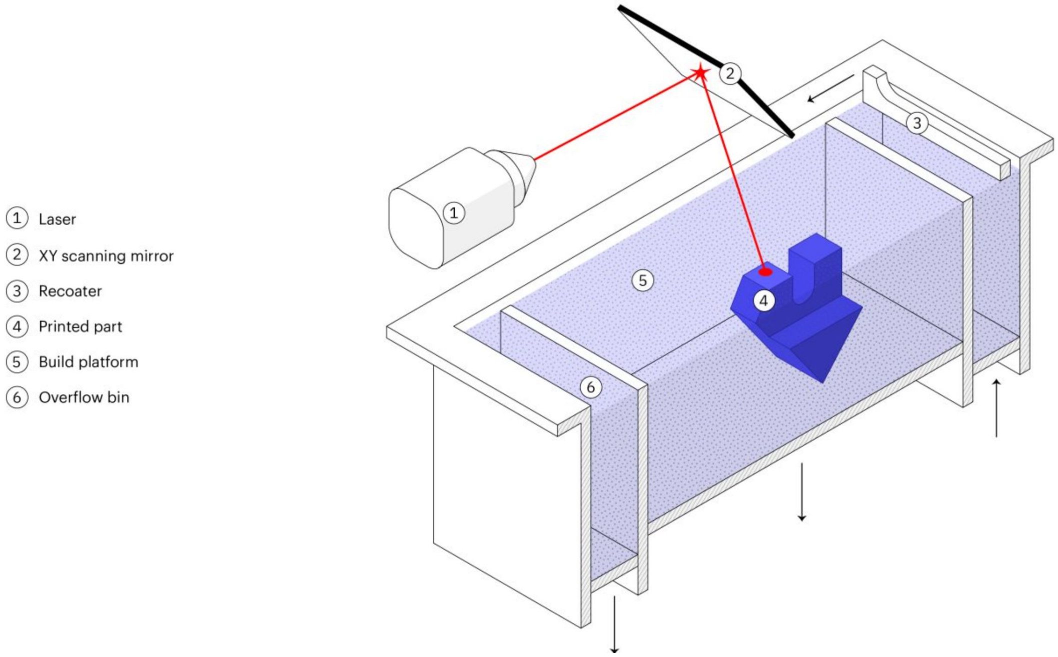


Figure 2-9: Selective Laser Sintering / Melting
Source: www.3dhubs.com/guides/3d-printing/

part. Because binding agent is laid down in the same fashion as an ink jet printer, the speed of this process is orders of magnitude faster than SLS/SLM and thus the cost per part is often similarly cheaper. A big challenge with ensuring uniform shrinking during the post-processing and porosity of end parts still exists.

Pros: High volume and speed; Cheaper than laser-based technologies; Can add color for plastics; High reusability of powder

Cons: Newer technology; Non-isotropic with binder; Uneven shrinkage during sintering for metals; Porosity of parts caused by addition of binding agent.

### 2.4.5 Some Current Challenges facing AM adoption

One of the largest challenges to incorporating additively manufactured parts within the vehicle product development process is the strict validation process. Because the component is formed in such a way that internal properties are inherently different from an identical component formed through traditional means, validating the design based on the additively manufactured component has inherent risks. False positives

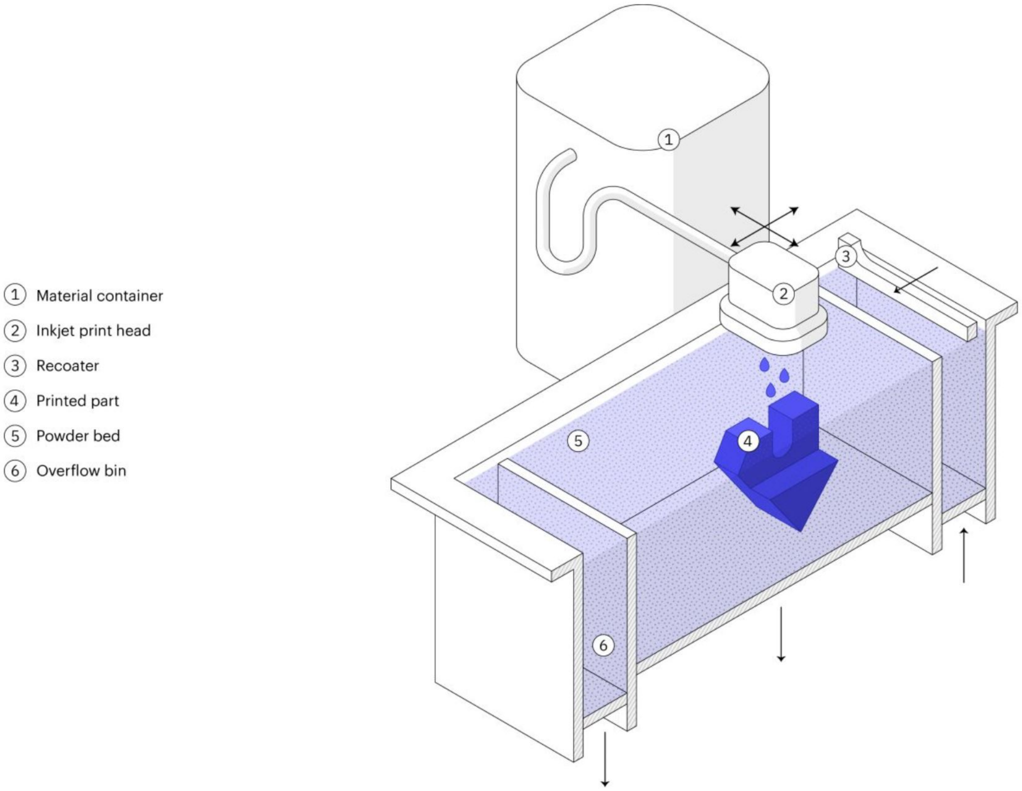


Figure 2-10: Binder Jetting
Source: www.3dhubs.com/guides/3d-printing/

- where an AM produced part pasts testing, but the identical part when produced by traditional means ultimately fails testing - is the most costly error.

Two strategies could help mitigate this risk. One would be to take the known difference in properties, such as strength and stiffness, and design the part with an appropriate engineering safety factor (i.e. make the design stronger than it needs to be). Another strategy would be to design the material and additive process to always be weaker than the traditionally manufactured material so as to never get that false positive. Each has pros and cons mostly centered around over-engineering. However, neither is currently feasible because of the variance inherent in many additive manufacturing processes. The same identical part built at different times with the same machine can have different properties due to the variability in making a part slowly layer by layer.

Aerospace and medical devices can use expensive CT scanners to determine the internal properties of printed parts. At the current cost of thousands of dollars for a CT scan (including amortized machine costs), this is not economically feasible for a normal automotive part. Either cheap scanning technologies or additive processes with less variability will be required to overcome this challenge.

This issue of validating a component based on a different manufacturing technology would also be partially mitigated if the final production part was to be printed using additive technologies. However, the cost and more importantly, throughput rate of additive manufacturing technologies limits its current applicability in automotive. With thin margins and production runs easily reaching the 100,000s, economies of scale dominate automotive sourcing decisions for most large automotive brands. Right now, the cost of small plastic pieces being in the $10s and small metal in the $100s, additive manufactured parts for any run greater than 100 often comes out to orders of magnitude greater than the cost of traditionally manufacturing these components. When binder jetting or similar additive technologies with high throughput and lack of expensive laser technologies mature, that equation may change. However, currently additive manufacturing is not ready economically for mass production use.

Even when the above obstacles are overcome, the final challenge of education and training remains. Designing a part for additive (DFAM), whether it is a prototype that will be traditionally manufactured, or for a final use AM part, is a different knowledge base and skill set that engineers will need to learn. Each AM machine has its own proprietary software, steps, quirks, and often materials. Standardization of these processes so that a design engineer can design a part without knowing exactly which machine will build the final part will be key to mass industry acceptance of AM within their processes.

# Chapter 3

# Literature Review

Uses of additive manufacturing within capital intensive industries such as automotive and aerospace have been growing within the past decade and is of increasing interest. However, most of the published studies and articles focus on its use for optimizing and creating previously impossible parts through designing for additive manufacturing (DFAM). When reviewing literature instead on the use of AM for rapid prototyping within product development, most articles focus on its use with low-volume, high-cost industries, like aerospace and medical devices, or small consumer products. Few articles discuss the use of additive manufacturing for creating complex hardware components that will eventually be produced at scale using traditional manufacturing processes. Regardless, in section 3.1 I will introduce some relevant literature on the use of AM within industry.

As mentioned previously in section 2.3, Agile methodologies have become the defacto software development paradigm. Just within the last couple years, interest in how to apply this family of methodologies to hardware development has started to be explored. The companies most interested in this make hardware components with embedded software, such as biomedical devices and products that would be described as being part of the 'internet of things'. They need their hardware designs to move at the speed of their software development. In Section 3.2, I will present relevant literature about applying agile methodologies to hardware. Most of these papers focus on creating singular devices with embedded software. Besides articles written by Cooper et al. on his theoretical Hybrid Agile-Stage-Gate process, the literature does not explore what an enterprise-level system would look like for a product that has thousands of components, only some of which have software dependencies, such as an aircraft or automobile. Additionally, while these papers all acknowledge the requirement for rapid physical prototyping to enable this agile-like hardware development, none explore in-depth how advances within additive manufacturing would enable that.

In the final section of this Literature Review, I will introduce papers on Product Development Process Design. This will include the Design Structure Matrix model I will be using to analyze a theoretical hardware development process and how using additive manufacturing to implement agile-like methodologies could improve the time, cost and hence ultimate performance of that process.

## 3.1 Additive Manufacturing Use within Capital Intensive Hardware Industries

According to Berman (2012), AM technologies have gone through three evolutionary phases: product designers employing AM technologies to produce prototypes of new designs, manufacturers using AM in creating finished parts, and the final (theoretical) phase of consumers using 3D printers to produce their own finished goods. Niaki and Nonino (2017) used this concept as the basis for their literature review of AM within the lens of management studies. As discussed earlier in this thesis, the focus of AM prototyping for the past few decades has been on visual design and geometric fit. But as additive manufacturing technologies, especially in metal, have evolved, the use within functional and final products are now feasible. Mellor et al. (2014) and Pour et al. (2016) discuss the implementation of AM within this context. Their focus quickly goes to the exciting concept of virtual supply chains as well as the product improvements that become possible though DFAM, such as light weighting and the combination of multiple previously assembled parts into one. Baumers et al. (2016)

also talks about the technology advances within 3D printing as a jump from rapid prototyping (which was necessitated by market-pull) to finished manufacturing (which is a technology-push). The increased functionality of 3D printed parts is the reason to transition from that phase one of prototyping to the phase two of manufacturing. Not discussed in depth in any of the current literature I found, however, is how this functionality also enhances prototyping and how it could be used to fundamentally improve hardware product development.

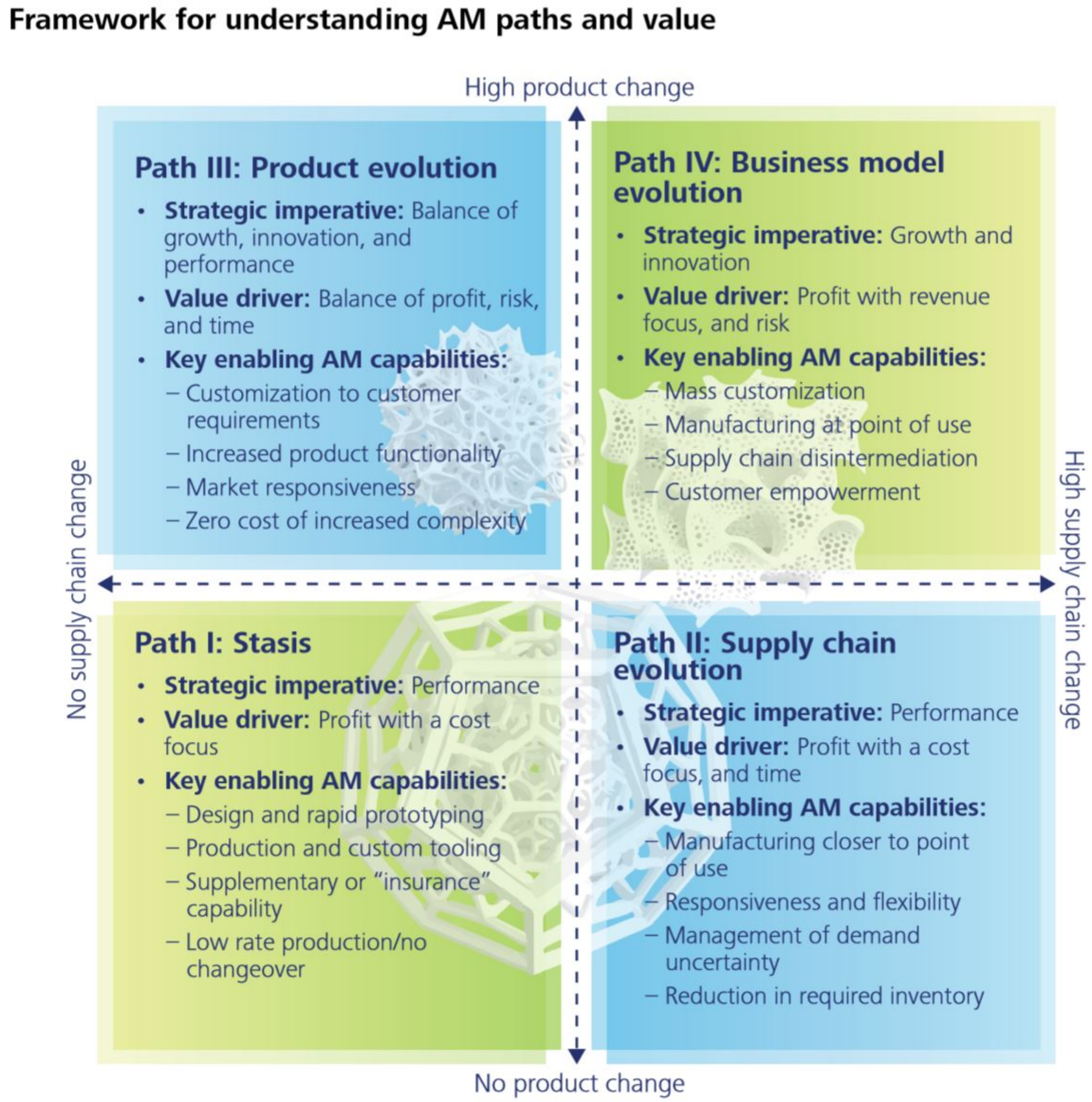
In a Harvard Business Review article, Richard D'Aveni states that the 3D printing revolution is at a cusp and that companies should not wait to "put a toe in the water" (D'Aveni, 2015).

> *The common theme here is small, incremental steps. In all three approaches, engineers are being given fascinating new puzzles to solve without having their world upended by still-evolving methods and materials, thus minimizing risk and resistance to change. It is up to more-senior managers to maintain the appropriate level of pressure for taking each successive step. As they push for further adoption, they should allow naysayers to explain why 3-D printing isn't right for a given part or process, but then challenge them to overcome that roadblock. Traditionalists will always be quick to tell you what 3-D printing can't do. Don't let them blind you to what it can.* - D'Aveni, 2015, p.47

However, if the thought is that the only desirable end goal for a 3D printed part is an end-use product, many companies will be loath to put in the investment before the technology is ready for that. I am advocating through this thesis that the logical next step for industries that are producing at scale is to be advancing 3D printing's use in product development beyond design and into functional prototypes before waiting for large-scale end-use to be ready. Piazza et al. (2017) discusses the cost curve of AM versus traditional manufacturing and comes to the conclusion that: "Bulk production of simple component and parts for consumer product will most likely never foresee a future with AM due to the nature of the process and the physical speed limitation of the machines used in the process" (p. 10). They state that only low to medium production volumes will be affected. However, those high production volume products require low to medium volumes of prototypes and validation units.

Curran et al. (2016) details how the company *Local Motors* used AM to make a pre-production chassis (or a 'mule' in automotive speak) for powertrain development and testing. To put this initiative in context, Giffi et al. (2014) within a Deloitte University Press article lays out four paths for automotive companies to take in implementing AM technologies. They call them Stasis, Supply Chain Evolution, Product Evolution, and Business Model Evolution. See Figure 3-1.

As can be inferred by the title of Path I, 'Stasis', this use of AM in rapid prototyping is considered by the authors to be the least desirable. But what the authors are missing is that a fundamental change of how hardware is designed and prototyped could lead to business model changes without having to create a completely new product nor disrupting your whole supply chain. What it can do is enable more innovation within a company's products. Candi and Beltagui (2019) attack that innovation topic in their paper and conclude that "using 3DP in innovation is more likely to be effective for businesses that face greater turbulence in their operating environment. This is because the principal benefits of 3DP stem from its ability to enable flexible responses to uncertainty" (p. 72). Great turbulence is exactly what is happening within mobility. The path to that innovation is incorporating Agile hardware development. Relevant literature on applying the Agile methodologies to hardware are presented in the next section.



**Framework for understanding AM paths and value**

High product change

**Path III: Product evolution**

- **Strategic imperative:** Balance of growth, innovation, and performance
- **Value driver:** Balance of profit, risk, and time
- **Key enabling AM capabilities:**
  - Customization to customer requirements
  - Increased product functionality
  - Market responsiveness
  - Zero cost of increased complexity

**Path IV: Business model evolution**

- **Strategic imperative:** Growth and innovation
- **Value driver:** Profit with revenue focus, and risk
- **Key enabling AM capabilities:**
  - Mass customization
  - Manufacturing at point of use
  - Supply chain disintermediation
  - Customer empowerment

No supply chain change

High supply chain change

**Path I: Stasis**

- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus
- **Key enabling AM capabilities:**
  - Design and rapid prototyping
  - Production and custom tooling
  - Supplementary or "insurance" capability
  - Low rate production/no changeover

**Path II: Supply chain evolution**

- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus, and time
- **Key enabling AM capabilities:**
  - Manufacturing closer to point of use
  - Responsiveness and flexibility
  - Management of demand uncertainty
  - Reduction in required inventory

No product change

Figure 3-1: AM Implementation Paths

Source: Mark Cotteleer and Jim Joyce, "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," Deloitte Review 14, January 2014.

## 3.2 Agile Methodologies within Hardware

As in introduced in Section 2.3, the *Agile Manifesto* proposed a PDP with quick development iterations that respond efficiently and effectively to customer feedback and testing (Beck et al., 2001). Since then, software development has been taken over by Agile methodologies (Brhel et al., 2015). There has been numerous literature about the benefit of iteration within product development. Wynn and Eckert (2017) compile a lot of that literature as well as propose a set terminology or taxonomy to describe the different types of iteration that happen within design and development. This will be discussed in greater detail in Chapter 4.

Applying this framework to hardware, where creating minimum viable products is more expensive and slow, is not trivial. Naturally, the first type of hardware products to attempt to apply Agile methodologies were hardware pieces that had embedded software such as network servers or high-tech medical devices. The product developers were looking to match the speed and cadence of their hardware development to that of their software. In other words, "How do you get hardware to move at the speed of software?" Shatil et al. (2010) and Kaisti et al. (2013) document some of those early forays into agile hardware development in embedded software systems. Mirachi et al. (2017) conducts an impressive side-by-side comparison on the benefits of agile methodology on an aircraft embedded system.

In the end, the differences between software and hardware development cannot be glossed over and you cannot simply apply the exact same practices to both. Albers et al. (2019) attempts to define what 'agility' even means within the context of hardware development. Musawir et al. (2020) discusses the importance of creating a project governance and defining those practices, even if the governance is more guidelines than rules. Thompson (2015) for the company CPrime wrote a white paper that tries to guide the creation of a project governance that focuses on applying the popular Scrum method to hardware development. In the trade magazine Agilevox, the results of a trial of this framework at ThermoFisher is presented (Thompson, 2016).

Ultimately, Thompson states that hardware inherently moves slower than software, so you should just embed multiple software iterations within a hardware iteration and be a little "softer" with some of the Scrum requirements, such as having work on a particular effort not span multiple sprints. But how can you make hardware prototyping move faster to enable these sprints? I contend AM is a necessary ingredient to doing that, especially when dealing with new designs that cannot be cobbled together with various off-the-shelf components. However, the literature out there discussing AM's role within agile hardware development is very sparse. Nguyen-Duc et al. (2018, 2019) discuss in both papers how start-ups they studied that did Agile hardware development often utilized 3D printers. But I could not find any literature whose subject focused on how AM enables Agile hardware development or what that process would look like.

Another issue with the current literature regarding Agile hardware development is that most of it does not apply to a large manufacturing company, such as automotive. Agile methodologies, even with software, have issues with scaling when your development team grows beyond seven to ten members. That is why follow-on concepts such as SAFe (Scale Agile Framework) and LeSS (Large Scale Scrum), as well as a logical extension of Agile beyond development to include operations, called DevOps, have been created and gained popularity within the last five or so years within the software industry. These frameworks apply Agile methodologies within the context of a larger and often more bureaucratic organization. A few papers discuss how a large hardware company might apply these larger Agile frameworks, including Hohl et al. (2018) and Durisic and Berenyi (2019), who both looked specifically to automotive. However, both these papers keep their scope to using scaled Agile methodologies within the embedded subsystems of an automobile. And as early studies, it is not quite clear how the faster development time frame of this embedded system integrates with the development of the complete automobile.

What happens when not every component can apply agile methodologies? This is the case with an automobile, which due to the economics of a product with over 10,000 parts, re-use and carryover of components is essential to make a vehicle affordable for the consumer. Marchionne, of Fiat Chrysler Automobile fame, famously laid out this need for more economies of scale, to include sharing of components between car makers, in a presentation entitled *Confessions of a Capital Junkie* (Marchionne, 2015). So if just slowing down Agile and applying it to hardware is not the answer, what could be a method to find a new process that takes advantage of Agile whenever possible, but lives in the reality of the design and production constraints of certain hardware components? To help find that answer, I will present literature on designing product development processes in the next section.

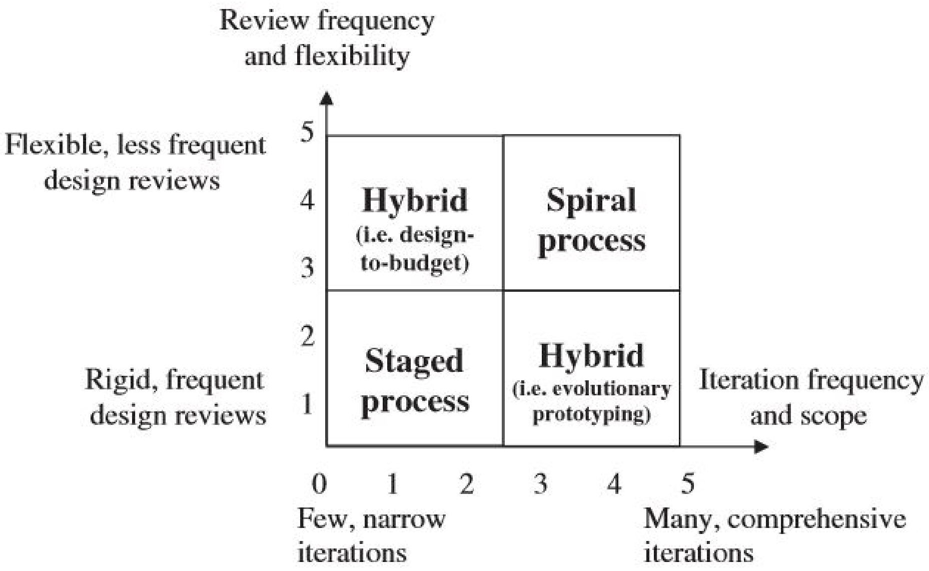
## 3.3 Product Development Process Design

Unger and Eppinger (2011) discuss how the flavor of the product development process should be determined by how flexible (or in other words, how dynamic) a project and its requirements are and how frequent the design iterations are. See Figure 3-2.

In the current status of automotive development, the project is inflexible and the iterations infrequent, hence the Phase-Gate process as described in section 2.2. And Browning (2018) lays out solid reasoning for that. He concludes, "Despite the appeal of agile approaches in many situations, it is wasteful and dangerous to 'muddle through' and 'reinvent the wheel' on each PD project." That may be true if you are just creating evolutions of the same product, which is what has happened within the automobile industry for the last half century. However, that slow and steady pace of automobile evolution is becoming competitively untenable. The sharing economy and the speed of technology innovation (brought in large part by Agile software development) means that the automobile industry is becoming the greater mobility industry. And the mobility industry is very vulnerable to, for lack of a better term, disruption.

Maisey and Dick (1996) explore what I think are some prescient concepts for the time in stating that the speed of defect detection is key to a successful product development process. Both the Waterfall and V model of product development are inherently poor at detecting defects, since development, prototyping and testing are so separated. With electrification, the connected Internet of Things, and autonomous

*D. Unger and S. Eppinger*


Review frequency and flexibility
Flexible, less frequent design reviews
Rigid, frequent design reviews
5
4
3
2
1
Hybrid (i.e. design-to-budget)
Spiral process
Staged process
Hybrid (i.e. evolutionary prototyping)
Iteration frequency and scope
0
1
2
3
4
5
Few, narrow iterations
Many, comprehensive iterations

PDP comparison based on common review and iteration characteristics.

Figure 3-2: Quad of PDP Types
Source: Unger and Eppinger, 2011

vehicles on the near horizon within automotive, automobile companies will be pushed to areas outside of their expertise. Trial and error will be required and a car company cannot afford slow detection of those inevitable errors. So, if we first accept that a car with thousands of reused parts is not as flexible as software or a small hardware component, but that increased design iterations improve innovation, this would push you to the hybrid development process at the bottom right of Figure 3-2. What would a process like that look like?

Eklund and Bosch (2012) take a stab at that. More explicitly, the self-described inventor of the Stage-Gate process - Robert G. Cooper, describes an evolution of his process in the age of Agile (Cooper and Sommer, 2018). Sommer et al. (2015) explores some case studies and early results of using Cooper's new method, which he calls a *Hybrid Agile-Stage-Gate Process.* But once again, the literature describes a process that takes advantage of the ability for hardware to be prototyped quickly, but glosses over exactly how certain hardware components are able to be iterated quickly and how those details would affect the overall hybrid development process.

And more importantly, most of these hybrid processes describe Agile iterations that exist wholly within strict phases. Figure 3-3 is a graphical description of such a hybrid process. One quickly sees that in this case, the whole project will only go as fast as the slowest of either the Agile iterations or the traditional Phage-Gate process. Additionally, they do not allow iterations to span gates. That is a benefit to the traditional desire for control of a process, but that clearly is at the expense of iterative innovation.

If a subset of your components, but not all, could be prototyped quickly due to technologies such as 3D printing, how would you create a combined Agile Phase-Gate Process that enables those components to have design freedom while still keeping review gates for those components that do not have such freedoms? And how could you tailor that process to the unique characteristics of a given project, as well as to the quickly evolving capabilities of additive manufacturing? A powerful tool to analyze PDPs and help answer those questions is the Design Structure Matrix (DSM).

Eppinger and Browning (2012) in their textbook *Design Structure Matrix Methods*

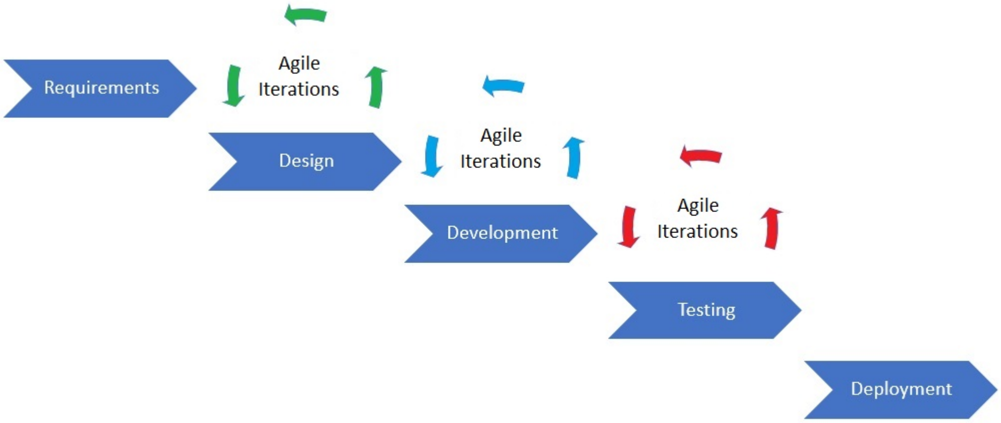


Figure 3-3: Hybrid Agile-Phase-Gate Depiction

*and Applications* describe in detail what a DSM is and how the flexible tool can be used in various contexts. In the most basic of terms, a DSM maps out the various dependencies within a product and a product development process. See Figure 3-4. It can be as simple as showing that a relationship does or does not exist between two processes, but can get more complex to show details like the magnitude of that relationship and the empirical or predicted probability that a change started in one process will reverberate to changes in its various interdependent processes.

Browning (2016) does a very thorough literature review of the use of DSM within different academic studies and industry papers. A particularly interesting paper is their own article on how DSM analysis was used to re-architect a product development process based on mapped out dependencies to improve the predicted cost and schedule of that project (Browning and Eppinger, 2002). Key to that is determining the risk relationships between components and processes. Yan-Ling et al. (2017) explores a mathematical strategy to help determine that.

DSMs will be used heavily in later chapters to analyze and simulate the theoretical performance of PDPs. Chapter 5 will go into futher detail in explaining the mechanics of a DSM and how it is used.

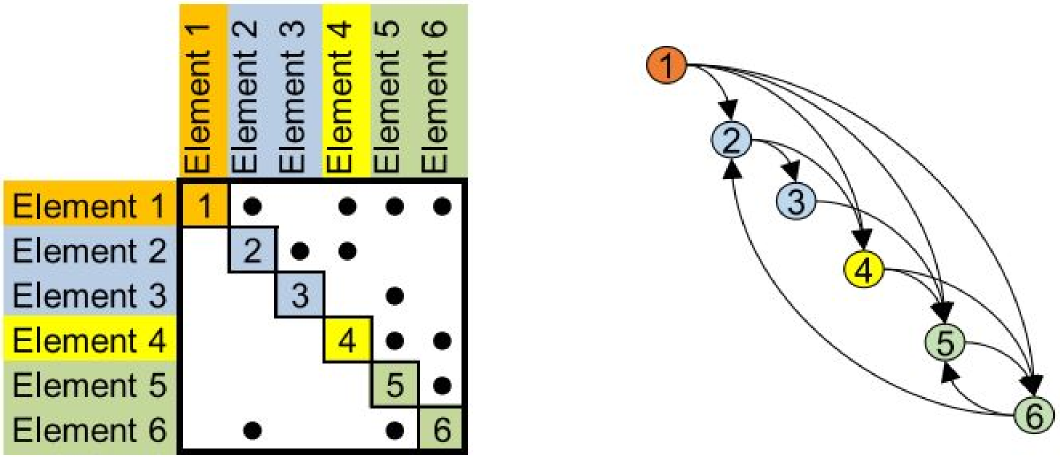


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Figure 3-4: Example of a binary DSM (IC convention), with optional row and column labels, and its equivalent node-link diagram (directed graph)

Source: Browning, 2016

## 3.4 Literature Review Wrap-Up

In this chapter, we introduced and discussed relevant literature within three broad topics: Additive Manufacturing, Agile Hardware Development, and Product Development Process Theory. I aim in the rest of this thesis to explicitly connect them in a way that is novel and hopefully meaningful. I aim to show how current and future advances in additive manufacturing can be used to smartly enable Agile methodologies within a greater complex hardware product development process.

# Chapter 4

# Analysis of Planned and Unplanned Iterations within a Product Development Processes

Before delving into an example product development process and how iteration and additive manufacturing could improve it, it is important to define what iteration within a product development process actually is. Wynn and Eckert (2017) create a useful taxonomy of iteration within the design and development process. This chapter discusses some of those different types of iterations presented in that paper that exist within a product development process. This chapter also discusses how a traditional Phase-Gate process handles these types of iterations versus an Agile process.

Wynn and Eckert break down iteration into three categories, based on its intended outcome:

1. *Progressive* iterations refine a solution. This type of iteration is required due to the uncertainty of a problem and its solution and the need to decompose those complex problems.

2. *Coordination* iterations help bring together multiple workflows into a single solution. This type of iteration is required in multi-team processes or when there are overlapped dependent tasks

3. *Corrective* iterations are the generally undesirable but often unavoidable rework that happens in response to unplanned adverse events or newly revealed information

The focus of the model that will be presented and analyzed in the next few chapters will be on how additive manufacturing can specifically enable parallel *progressive* iterations in a product development process. However, understanding the other two types of iterations are important in how additive manufacturing can mitigate the risks involved with the integration of an Agile and Phase-Gate process.

## 4.1 Progressive Iterations

Progressive iteration is what is at the core of Agile development. Of the five types of progressive iterations Wynn and Eckert delineate in Figure 4-1, the two most interesting in the context of this thesis are *Convergence* and *Refinement* iterations. Convergence is in essence what is required to find an unknown solution and refinement is what is needed to improve that solution. Convergence is at the core of repeated Agile sprints and refinement is the reason there is a time bounded box on those sprints. Otherwise, you could refine forever.

These types of iteration also happen in a traditional Phase-Gate process. However, any convergence or refinement in a Phase-Gate process is constrained to the current phase. By definitions of a gate, there is no going back. The Hybrid Agile-Stage-Gate process that Cooper and Sommer (2018) propose does not break that constraint. The major innovation they propose is having Agile sprints within the current phase.

Being constrained is not necessarily a bad thing and is in fact by-design in a Phase-Gate process. Going back to revisit a problem that has already passed gate review is costly and possibly unnecessary. However, one thing to consider is that in a development process that takes multiple years, like an automobile, the requirements stage that defined what your product can do based on your stakeholders' desires can be fixed years before your product is delivered to your customer.

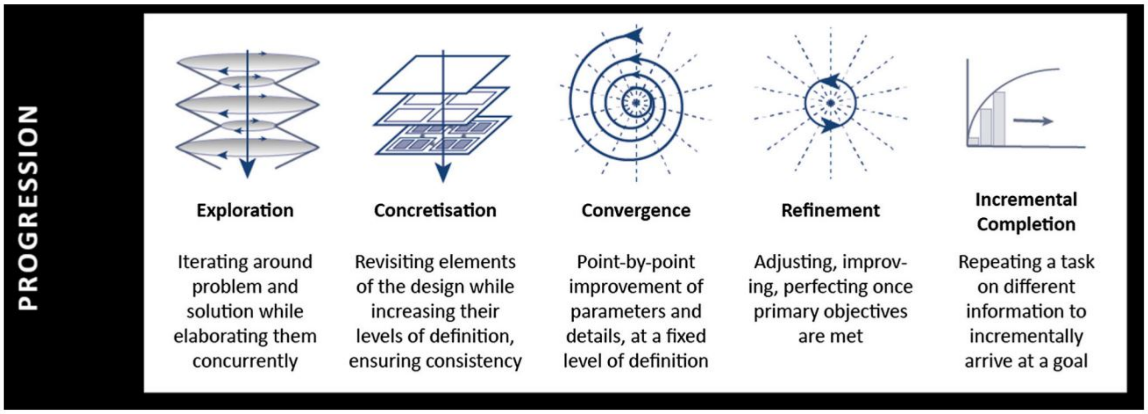

PROGRESSION
Exploration
Iterating around problem and solution while elaborating them concurrently
Concretisation
Revisiting elements of the design while increasing their levels of definition, ensuring consistency
Convergence
Point-by-point improvement of parameters and details, at a fixed level of definition
Refinement
Adjusting, improving, perfecting once primary objectives are met
Incremental Completion
Repeating a task on different information to incrementally arrive at a goal

Figure 4-1: Progressive Iterations
Source: Wynn and Eckert, 2017

What happens when your customer desires change during that long time frame or technology has advanced and would allow for greater capability in your product? In the current Phase-Gate system, nothing can happen and those customer desires and new technologies can only be incorporated into the next project that has yet to pass the requirements gate. If a certain capability is not technologically ready by the time the automobile's requirement gate is happening, that capability is not included. However, a capability can become technologically ready between the time of that requirement gate review and the time the automobile is being manufactured or still engineered. This is a byproduct of technological innovation happening at the speed of Agile development, with a takt time of months, while a complex hardware product like the car is happening at the speed of a Phase-Gate process, with a takt time of years. This bakes in a three to four year lag in what the market wants or what is technologically feasible and the technology that is being sold with current automobiles.

This lag is becoming more and more important due to more demanding consumer requirements. With the evolution of technology within automobiles, consumers are basing their buying decisions more and more on what type of technological capabilities and features an automobile has. Electrification and autonomous technologies are the extreme versions of this. But smaller components including cell phone integration and active safety features can also be vital in swaying consumers towards or away from your brand. An industry study found that "half, or more, of drivers are willing to sacrifice on vehicle color, style, and brand in order to get the latest technology" (Cox, 2017). The automobile company that can integrate newer technologies sooner will have a huge competitive advantage. This ability is even more critical when developing an autonomous vehicle, a topic that will be discussed a little more at the end of this thesis.

How can you redesign the automobile's product development process to allow for certain critical components to revisit the requirements stage closer to product deployment and launch? This exact question will be explored in the following chapters with a solution proposed that is enabled via additive manufacturing.

## 4.2 Coordination Iterations

Coordination is the next type of iteration that will be discussed. See Wynn and Eckert's diagram in Figure 4-2, specifically *Negotiation* and *Parallelisation.* In a large and complex project, like an automobile, negotiation and parallelisation are baked into the process. These type of iterations are inherent when you have multiple teams working on sets of components that affect and interface with other sets of components. This type of iteration can be mitigated with modular architectures where you define the interface standards. While there has been some past work and continues to be some work on making automobiles like this - the 'skateboard' chassis being used by

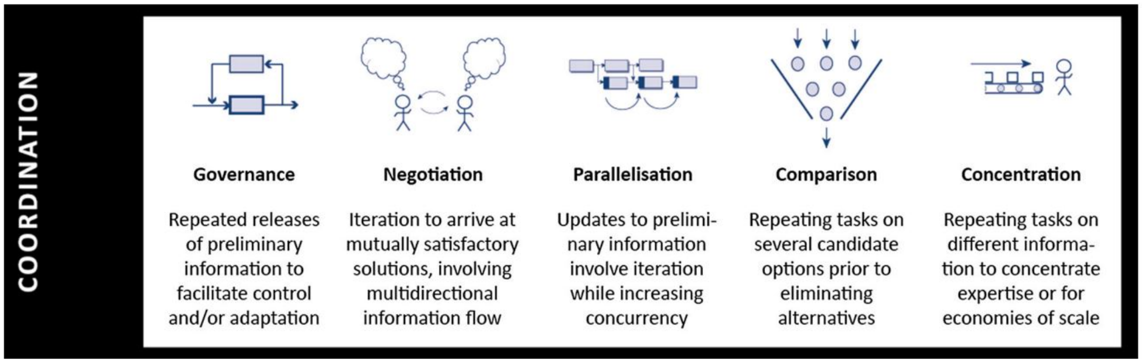

COORDINATION
Governance
Repeated releases of preliminary information to facilitate control and/or adaptation
Negotiation
Iteration to arrive at mutually satisfactory solutions, involving multidirectional information flow
Parallelisation
Updates to preliminary information involve iteration while increasing concurrency
Comparison
Repeating tasks on several candidate options prior to eliminating alternatives
Concentration
Repeating tasks on different information to concentrate expertise or for economies of scale

Figure 4-2: Coordination Iterations
Source: Wynn and Eckert, 2017

some electric vehicle manufacturers is one example - almost all vehicles on the road are not manufactured in a modular way. This is for a myriad of reasons, but one is that investment in a set module standard is very expensive and in the end, can limit a company's flexibility and agility once they are locked into a specific modular architecture.

So instead, various teams work in parallel and come together periodically to negotiate and figure out if developments and changes a team has made in one area affects the work of another. While making a whole car modular might not make sense, an argument will be presented later in this thesis for making a few known stable interfaces for key components. This will allow the proposed parallel development to proceed on those components with minimal risk of schedule costs due to unwanted coordination iterations required at time of integration. However, sometimes change even with the known stable interface would be required. Additive manufacturing would allow the flexibility of the component to be redesigned without the expensive costs associated with retooling.

## 4.3 Corrective Iterations

Finally, there is corrective iteration. Within Phase-Gate processes, this is the dreaded efforts often associated with *rework* and *churn*. See Figure 4-3. These words elicit

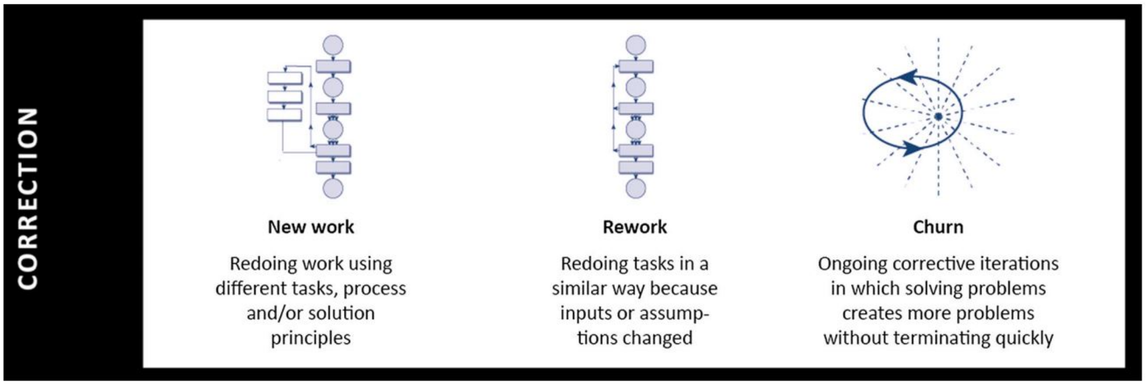

CORRECTION
New work
Redoing work using different tasks, process and/or solution principles
Rework
Redoing tasks in a similar way because inputs or assumptions changed
Churn
Ongoing corrective iterations in which solving problems creates more problems without terminating quickly

Figure 4-3: Corrective Iterations
Source: Wynn and Eckert, 2017

thoughts of greater costs and extended schedule. And sometimes this is true. In a perfect world, corrective iterations could always be avoided. It often comes late in the process where it is discovered that something had not been thought about or that an assumption was proven wrong. While each instance could be argued to be avoidable, in a large project, the existence of rework is statistically an inevitability. If the final design upon integration does have unforeseen issues, additive manufacturing allows for corrective changes to be made quickly within the time frame of a sprint, without costing the project too much schedule slip.

# Chapter 5

# Modelling and Simulating a Product Development Process with Design Structure Matrices

The rest of this thesis will use the Design Structure Matrix (DSM) to model and simulate the performance of proposed product development processes (PDP). This chapter explains the basic mechanics of how a DSM is used to model, analyze, and simulate a PDP. Much of this chapter is derived from Eppinger and Browning (2012) and Yassine (2004).

## 5.1 The structure of the matrix

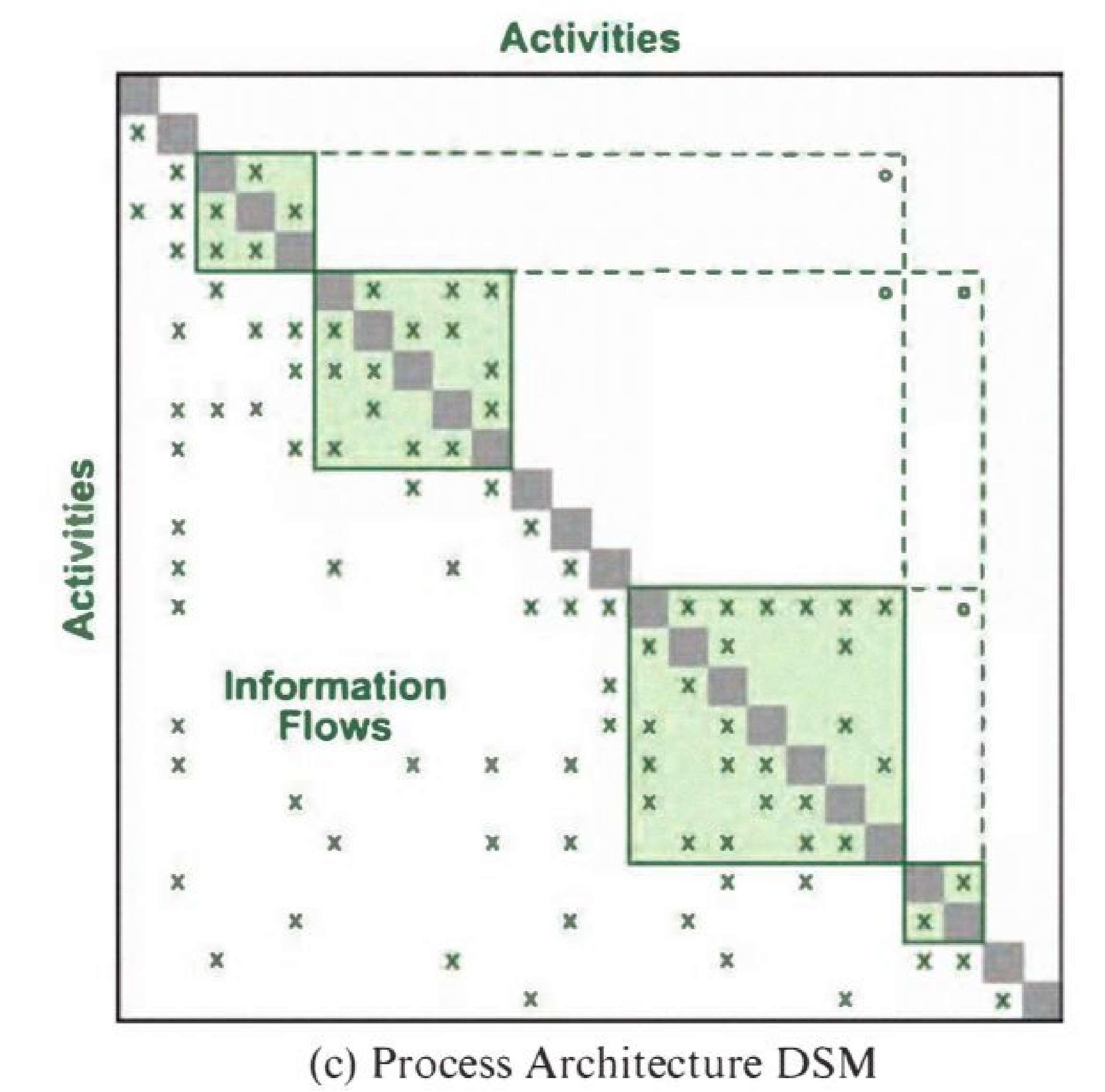
The Design Structure Matrix is a network modeling tool that maps out the interactions of elements within a system. It has been primarily used within the context of engineering management of complex systems. The concept of a DSM was created by Professor Don Steward of California State University, Sacramento in 1970. However, it did not have much industrial applications until it was used and enhanced by master's and doctoral students at MIT, many studying under Professor Steve Eppinger, in the early 1990s (Eppinger and Browning, 2012, p. 12-13). Since 1999 an annual conference around DSM has been held where academics and industry personnel share their insights and current uses.

At its core, a DSM is an $N$ x $N$ matrix that visually maps the interactions of N elements. Those elements could be physical components of a system (e.g. spark plug, fuel injector), processes of a PDP (e.g. finalize requirements of engine, build prototype), resources (e.g. designers, test engineers), or product functions (e.g. propulsion, cabin environment). Because this thesis is about the product development process, we will focus on DSMs that utilize that second family of elements – the process architecture DSM, which maps out flows of information or material between various process steps. See Figure 5-1

There are three basic interactions that can be mapped using a DSM: parallel, sequential, and coupled. You can see digraph representations of these interactions in Figure 5-2. The boxes $A$ and $B$ represent a process step within a PDP (e.g. Create Concept Sketches, Theme Approval). The arrows represent information flow or outputs required as inputs for the other step (e.g. a CAD model).

A DSM is able to present these relationships among many elements in one succinct matrix. A DSM has a row corresponding to each process in the system along with identical columns. The diagonal elements where the row and column are identical are not used, usually filled in with black. An $X$ or other mark in the other boxes then shows if those elements have an interaction or exchange of information. There are two possible conventions to show these relationships. I will use the original Inputs in Row (IR) convention. This means as you read across a row, the marks show the information or material inputs into that process. The marks along those process columns indicate the outputs of that process. The other convention (Inputs in Column or IC) is just the transpose of that. Figure 5-3 is the corresponding DSM representation of those three basic interactions shown in the previous digraph.

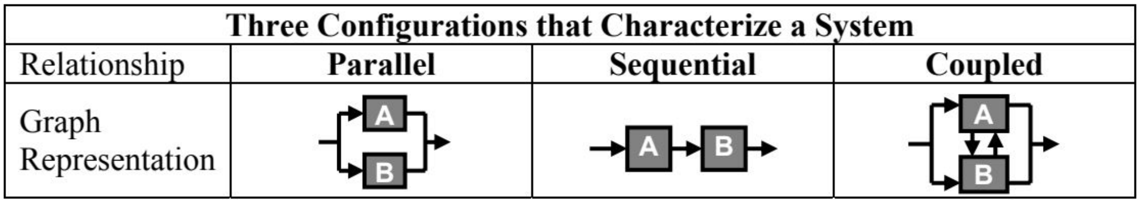
A more complex process is shown in Figure 5-4 with information flows first shown as a spaghetti graph and the same process shown in a corresponding DSM. The nodes in the spaghetti graph represent process steps and the arrows are information flows. The corresponding DSM maps that complex process with multiple overlapping lines into an organized matrix. The dotted lines are there just to explicitly show the



| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ | | | | | | | | | | | | | | | | | | | | | | | |
| x | ■ | | | | | | | | | | | | | | | | | | | | | | |
| | x | ■ | x | | | | | | | | | | | | | | | | o | | | | |
| x | x | x | ■ | x | | | | | | | | | | | | | | | | | | | |
| | x | x | x | ■ | | | | | | | | | | | | | | | | | | | |
| | | x | | | ■ | x | | x | x | | | | | | | | | | o | | o | | |
| | x | | x | x | x | ■ | x | x | | | | | | | | | | | | | | | |
| | | | | x | x | x | ■ | | x | | | | | | | | | | | | | | |
| | x | x | x | | | x | | ■ | x | | | | | | | | | | | | | | |
| | x | | | x | x | | x | x | ■ | | | | | | | | | | | | | | |
| | | | | | | | x | | x | ■ | | | | | | | | | | | | | |
| | x | | | | | | | | | x | ■ | | | | | | | | | | | | |
| | x | | | | x | | | x | | | x | ■ | | | | | | | | | | | |
| | x | | | | | | | | | x | x | x | ■ | x | x | x | x | x | x | | o | | |
| | | | | | | | | | | | | | x | ■ | x | | | x | | | | | |
| | | | | | | | | | | | | x | | x | ■ | | | | | | | | |
| | x | | | | | | | | | | | x | x | | x | ■ | | x | | | | | |
| | x | | | | | | x | | x | | x | | x | | x | x | ■ | | x | | | | |
| | | | | x | | | | | | | | | x | | | x | x | ■ | | | | | |
| | | | | | x | | | | x | | x | | | x | x | | x | x | ■ | | | | |
| | x | | | | | | | | | | | | | | x | | x | | | ■ | x | | |
| | | | | x | | | | | | | x | | | x | | | | | | x | ■ | | |
| | | x | | | | | | x | | | | | | | x | | | | | x | x | ■ | |
| | | | | | | | | | | x | | | | | | | | x | | | | x | ■ |

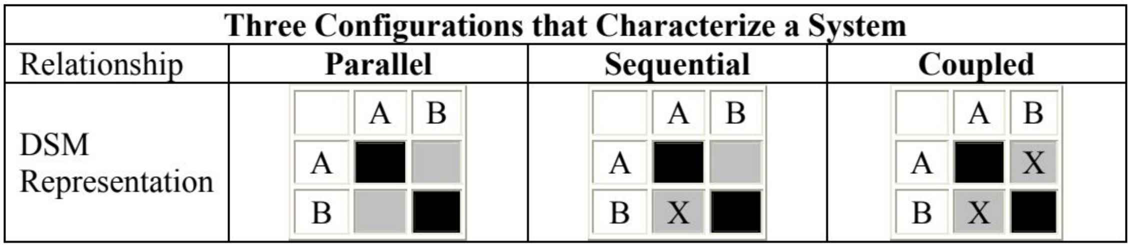
(c) Process Architecture DSM

Figure 5-1: A DSM mapping information or material flow between process steps
Source: Eppinger and Browning, 2012



| Three Configurations that Characterize a System | | | |
|---|---|---|---|
| Relationship | **Parallel** | **Sequential** | **Coupled** |
| Graph Representation | A<br>B | A B | A<br>B |

Figure 5-2: PDP Digraphs
Source: Yassine, 2004

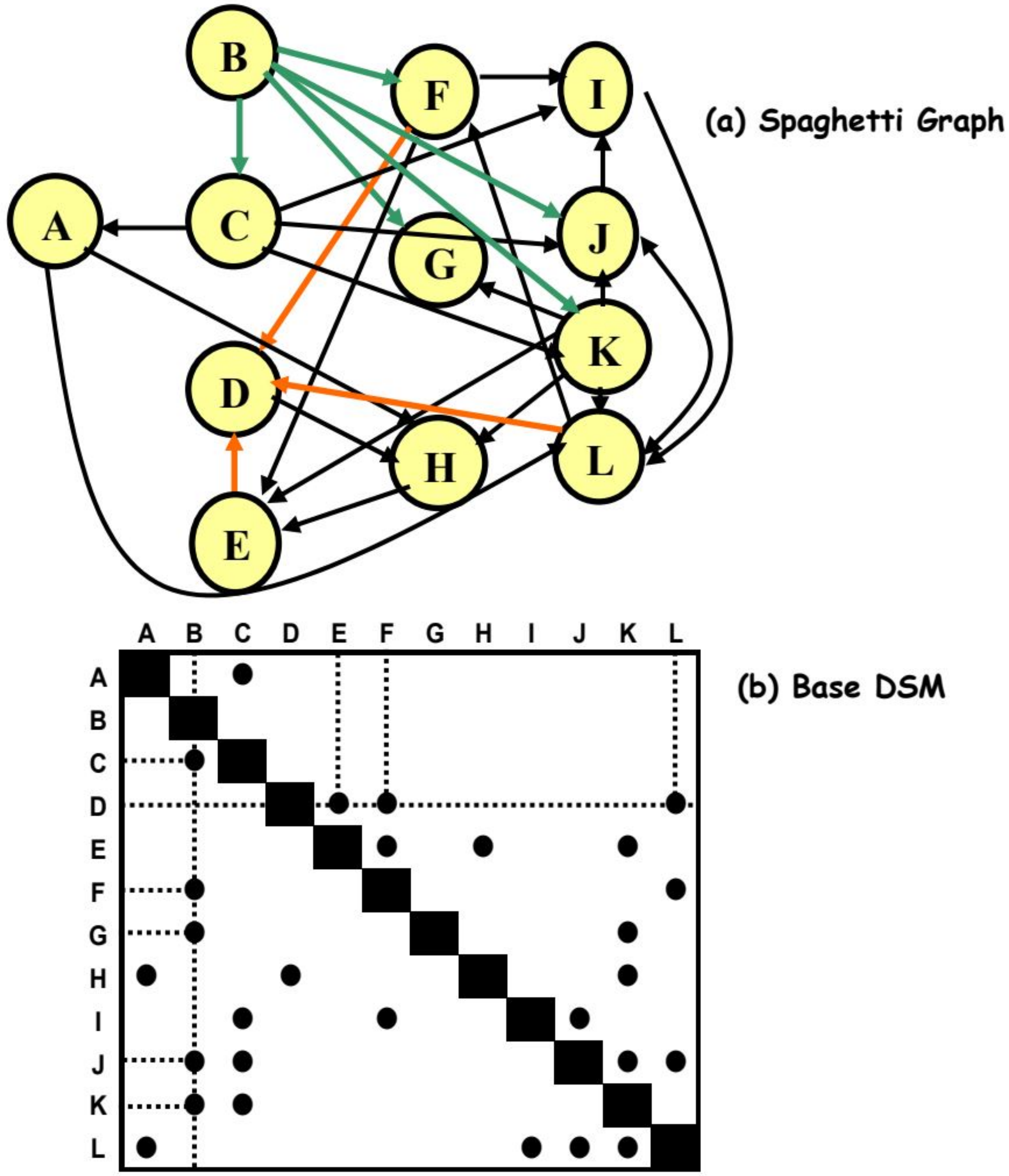


| **Three Configurations that Characterize a System** | | | |
|---|---|---|---|
| Relationship | **Parallel** | **Sequential** | **Coupled** |
| DSM Representation | A B<br>A ■ ▨<br>B ▨ ■ | A B<br>A ■ ▨<br>B X ■ | A B<br>A ■ X<br>B X ■ |

Figure 5-3: DSM Representation Examples
Source: Yassine, 2004

interactions highlighted in the spaghetti graph in green and orange. A key attribute of a DSM is the ability to quickly see where feedback loops exist. When you order the steps in the sequence that they will be started, marks above the diagonal show information feedback from a later step to an earlier step. This type of information flow will cause iteration or rework. Marks below the diagonal show standard sequential flow of information through the process.

Once you have all those relationships mapped out, there are several steps and algorithms that you can use to theoretically improve a PDP by rearranging the sequence of process steps. Yassine presents a good step by step explanation of these operations called *Partitioning, Tearing, and Banding.* However, for the purposes of this thesis, we are primarily utilizing a DSM to help determine the expected schedule of comparative processes with a set sequence.



|   | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | ■ |   | ● |   |   |   |   |   |   |   |   |   |
| B |   | ■ |   |   |   |   |   |   |   |   |   |   |
| C |   | ● | ■ |   |   |   |   |   |   |   |   |   |
| D |   |   |   | ■ | ● | ● |   |   |   |   |   | ● |
| E |   |   |   |   | ■ | ● |   | ● |   |   | ● |   |
| F |   | ● |   |   |   | ■ |   |   |   |   |   | ● |
| G |   | ● |   |   |   |   | ■ |   |   |   | ● |   |
| H | ● |   |   | ● |   |   |   | ■ |   |   | ● |   |
| I |   |   | ● |   |   | ● |   |   | ■ | ● |   |   |
| J |   | ● | ● |   |   |   |   |   |   | ■ | ● | ● |
| K |   | ● | ● |   |   |   |   |   |   |   | ■ |   |
| L | ● |   |   |   |   |   |   |   | ● | ● | ● | ■ |

Figure 5-4: DSM Example
Source: Yassine, 2004

## 5.2 Simulating a Product Development Process via DSM

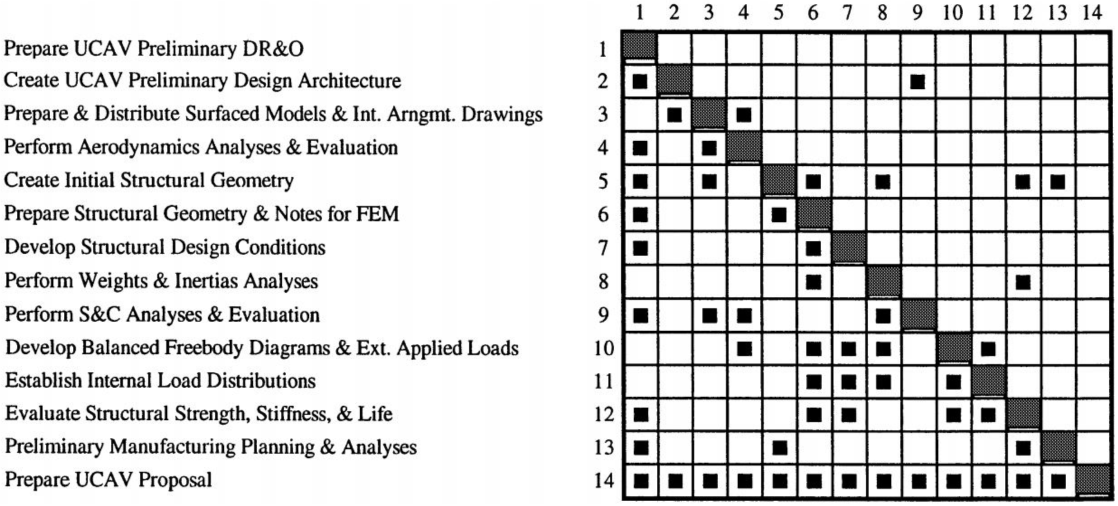
With some amplifying data on each process and the dependencies each $X$ represents, you can utilize a DSM to simulate the expected duration and costs of a product development process. This section will explain the required data and how it can be used, utilizing an example from an actual unmanned combat aerial vehicle's (UCAV) design process (Browning and Eppinger, 2002). See Figure 5-5.

Inserting representative numbers instead of $X$'s in a DSM, makes a Numerical DSM. One type of data you can have is the rework probability caused by information feedback. This number reflects the probability of one activity causing rework in another. Upper-diagonal elements represent the probability of having to loop back (i.e. iteration) to earlier (upstream) activities after a later (downstream) activity was performed. Lower-diagonal elements represent the probability of a second-order rework following an iteration (Smith and Eppinger, 1997). See Figure 5-6 for a version of the previous DSM with associated rework probabilities inserted.

The next set of data that would be beneficial would be the impact of the rework. If a task has to be redone due to new information from a follow-on task, often only a fraction of the task has to be reworked. This is called impact strength. See Figure 5-7.

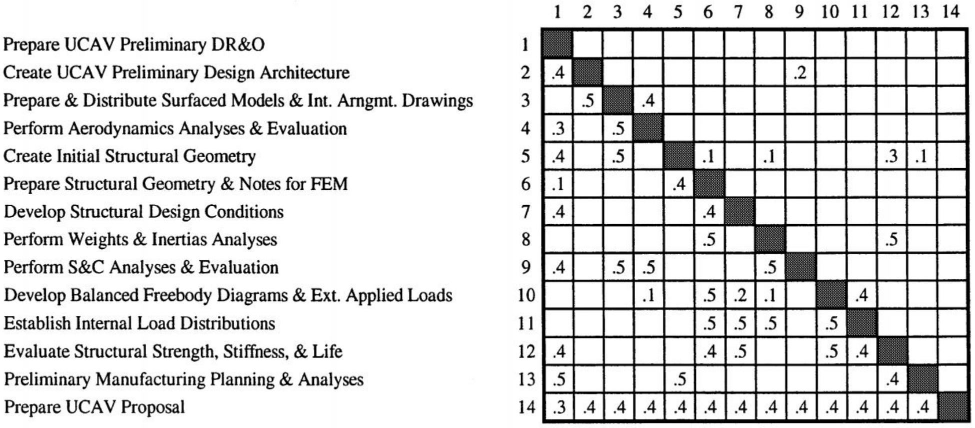
The final set of data needed to do a simulation is information on each task, such as expected duration, cost, and if there is an improvement curve (i.e. will subsequent iterations of the task be completed more quickly than previous ones due to inherent learnings from repeating the task?). See Figure 5-8 for a table with that information from the same UCAV example.

The *best*, *median*, and *worst* cost and duration values are used to model the random variable for task time as a triangular distribution. But other distributions could be used. Given all this information, you can run a Monte Carlo simulation that takes task length and cost values from the given distribution, combines it with the likelihood of rework and its impact value to give a distribution of possible length



| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prepare UCAV Preliminary DR&O | 1 | ▨ | | | | | | | | | | | | | |
| Create UCAV Preliminary Design Architecture | 2 | ■ | ▨ | | | | | | | ■ | | | | | |
| Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings | 3 | | ■ | ▨ | ■ | | | | | | | | | | |
| Perform Aerodynamics Analyses & Evaluation | 4 | ■ | | ■ | ▨ | | | | | | | | | | |
| Create Initial Structural Geometry | 5 | ■ | | ■ | | ▨ | ■ | | ■ | | | | ■ | ■ | |
| Prepare Structural Geometry & Notes for FEM | 6 | ■ | | | | ■ | ▨ | | | | | | | | |
| Develop Structural Design Conditions | 7 | ■ | | | | | ■ | ▨ | | | | | | | |
| Perform Weights & Inertias Analyses | 8 | | | | | | ■ | | ▨ | | | | ■ | | |
| Perform S&C Analyses & Evaluation | 9 | ■ | | ■ | ■ | | | | ■ | ▨ | | | | | |
| Develop Balanced Freebody Diagrams & Ext. Applied Loads | 10 | | | | ■ | | ■ | ■ | ■ | | ▨ | ■ | | | |
| Establish Internal Load Distributions | 11 | | | | | | ■ | ■ | ■ | | ■ | ▨ | | | |
| Evaluate Structural Strength, Stiffness, & Life | 12 | ■ | | | | | ■ | ■ | | | ■ | ■ | ▨ | | |
| Preliminary Manufacturing Planning & Analyses | 13 | ■ | | | | ■ | | | | | | | ■ | ▨ | |
| Prepare UCAV Proposal | 14 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ▨ |

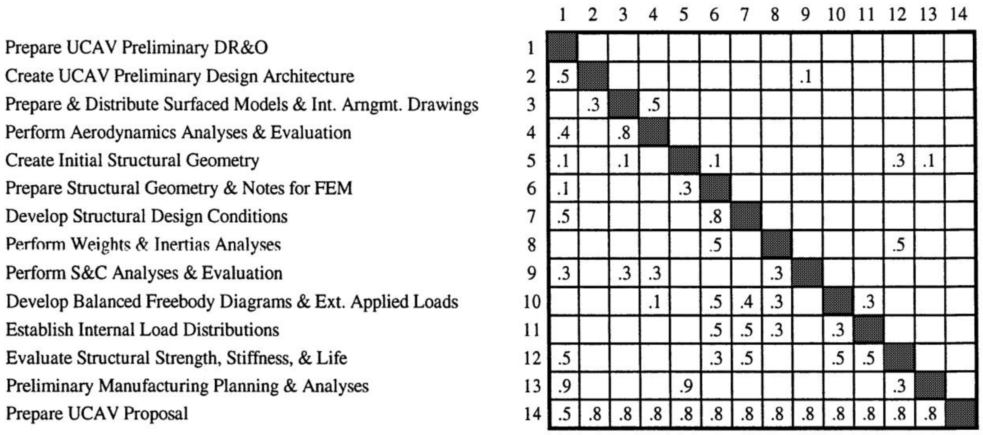
Figure 5-5: A DSM from a UCAV's preliminary design process
Source: Browning and Eppinger, 2002



| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prepare UCAV Preliminary DR&O | 1 | ▨ | | | | | | | | | | | | | |
| Create UCAV Preliminary Design Architecture | 2 | .4 | ▨ | | | | | | | .2 | | | | | |
| Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings | 3 | | .5 | ▨ | .4 | | | | | | | | | | |
| Perform Aerodynamics Analyses & Evaluation | 4 | .3 | | .5 | ▨ | | | | | | | | | | |
| Create Initial Structural Geometry | 5 | .4 | | .5 | | ▨ | .1 | | .1 | | | | .3 | .1 | |
| Prepare Structural Geometry & Notes for FEM | 6 | .1 | | | | .4 | ▨ | | | | | | | | |
| Develop Structural Design Conditions | 7 | .4 | | | | | .4 | ▨ | | | | | | | |
| Perform Weights & Inertias Analyses | 8 | | | | | | .5 | | ▨ | | | | .5 | | |
| Perform S&C Analyses & Evaluation | 9 | .4 | | .5 | .5 | | | | .5 | ▨ | | | | | |
| Develop Balanced Freebody Diagrams & Ext. Applied Loads | 10 | | | | .1 | | .5 | .2 | .1 | | ▨ | .4 | | | |
| Establish Internal Load Distributions | 11 | | | | | | .5 | .5 | .5 | | .5 | ▨ | | | |
| Evaluate Structural Strength, Stiffness, & Life | 12 | .4 | | | | | .4 | .5 | | | .5 | .4 | ▨ | | |
| Preliminary Manufacturing Planning & Analyses | 13 | .5 | | | | .5 | | | | | | | .4 | ▨ | |
| Prepare UCAV Proposal | 14 | .3 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | ▨ |

$\boldsymbol{DSM}_{\mathrm{xy1}}$ showing rework probabilities for UCAV process.

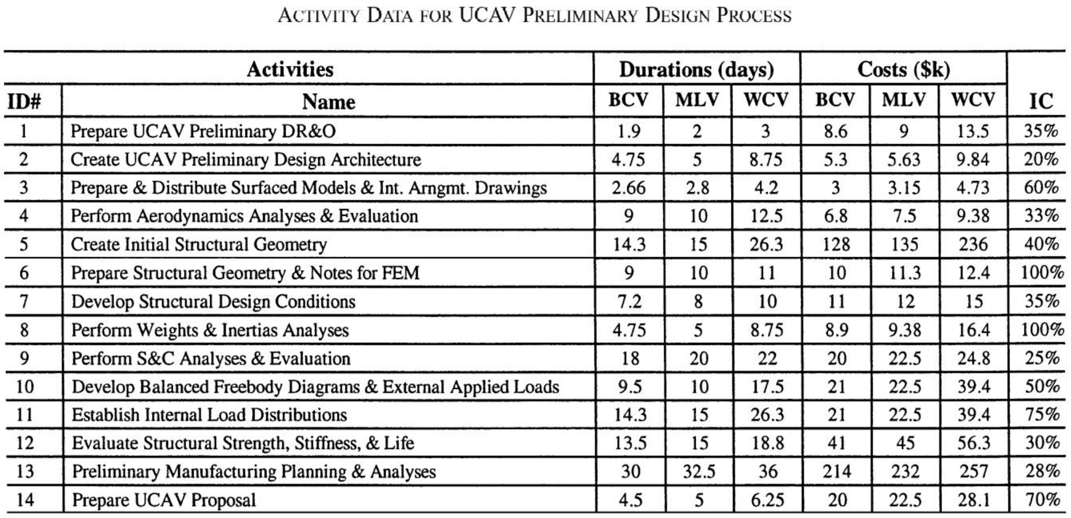
Figure 5-6: A numerical DSM representing rework probabilities
Source: Browning and Eppinger, 2002



|  |  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prepare UCAV Preliminary DR&O | 1 | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Create UCAV Preliminary Design Architecture | 2 | .5 | ▨ |  |  |  |  |  |  | .1 |  |  |  |  |  |
| Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings | 3 |  | .3 | ▨ | .5 |  |  |  |  |  |  |  |  |  |  |
| Perform Aerodynamics Analyses & Evaluation | 4 | .4 |  | .8 | ▨ |  |  |  |  |  |  |  |  |  |  |
| Create Initial Structural Geometry | 5 | .1 |  | .1 |  | ▨ | .1 |  |  |  |  |  | .3 | .1 |  |
| Prepare Structural Geometry & Notes for FEM | 6 | .1 |  |  |  | .3 | ▨ |  |  |  |  |  |  |  |  |
| Develop Structural Design Conditions | 7 | .5 |  |  |  |  | .8 | ▨ |  |  |  |  |  |  |  |
| Perform Weights & Inertias Analyses | 8 |  |  |  |  |  | .5 |  | ▨ |  |  |  | .5 |  |  |
| Perform S&C Analyses & Evaluation | 9 | .3 |  | .3 | .3 |  |  |  | .3 | ▨ |  |  |  |  |  |
| Develop Balanced Freebody Diagrams & Ext. Applied Loads | 10 |  |  |  | .1 |  | .5 | .4 | .3 |  | ▨ | .3 |  |  |  |
| Establish Internal Load Distributions | 11 |  |  |  |  |  | .5 | .5 | .3 |  | .3 | ▨ |  |  |  |
| Evaluate Structural Strength, Stiffness, & Life | 12 | .5 |  |  |  |  | .3 | .5 |  |  | .5 | .5 | ▨ |  |  |
| Preliminary Manufacturing Planning & Analyses | 13 | .9 |  |  |  | .9 |  |  |  |  |  |  | .3 | ▨ |  |
| Prepare UCAV Proposal | 14 | .5 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | .8 | ▨ |

***DSM***$_{\mathrm{xy2}}$ showing rework impacts for UCAV process.

Figure 5-7: A numerical DSM representing impact probabilities
Source: Browning and Eppinger, 2002



ACTIVITY DATA FOR UCAV PRELIMINARY DESIGN PROCESS

| Activities |  | Durations (days) |  |  | Costs ($k) |  |  |  |
|---|---|---|---|---|---|---|---|---|
| **ID#** | **Name** | **BCV** | **MLV** | **WCV** | **BCV** | **MLV** | **WCV** | **IC** |
| 1 | Prepare UCAV Preliminary DR&O | 1.9 | 2 | 3 | 8.6 | 9 | 13.5 | 35% |
| 2 | Create UCAV Preliminary Design Architecture | 4.75 | 5 | 8.75 | 5.3 | 5.63 | 9.84 | 20% |
| 3 | Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings | 2.66 | 2.8 | 4.2 | 3 | 3.15 | 4.73 | 60% |
| 4 | Perform Aerodynamics Analyses & Evaluation | 9 | 10 | 12.5 | 6.8 | 7.5 | 9.38 | 33% |
| 5 | Create Initial Structural Geometry | 14.3 | 15 | 26.3 | 128 | 135 | 236 | 40% |
| 6 | Prepare Structural Geometry & Notes for FEM | 9 | 10 | 11 | 10 | 11.3 | 12.4 | 100% |
| 7 | Develop Structural Design Conditions | 7.2 | 8 | 10 | 11 | 12 | 15 | 35% |
| 8 | Perform Weights & Inertias Analyses | 4.75 | 5 | 8.75 | 8.9 | 9.38 | 16.4 | 100% |
| 9 | Perform S&C Analyses & Evaluation | 18 | 20 | 22 | 20 | 22.5 | 24.8 | 25% |
| 10 | Develop Balanced Freebody Diagrams & External Applied Loads | 9.5 | 10 | 17.5 | 21 | 22.5 | 39.4 | 50% |
| 11 | Establish Internal Load Distributions | 14.3 | 15 | 26.3 | 21 | 22.5 | 39.4 | 75% |
| 12 | Evaluate Structural Strength, Stiffness, & Life | 13.5 | 15 | 18.8 | 41 | 45 | 56.3 | 30% |
| 13 | Preliminary Manufacturing Planning & Analyses | 30 | 32.5 | 36 | 214 | 232 | 257 | 28% |
| 14 | Prepare UCAV Proposal | 4.5 | 5 | 6.25 | 20 | 22.5 | 28.1 | 70% |

Figure 5-8: UCAV Activity Details
Source: Browning and Eppinger, 2002

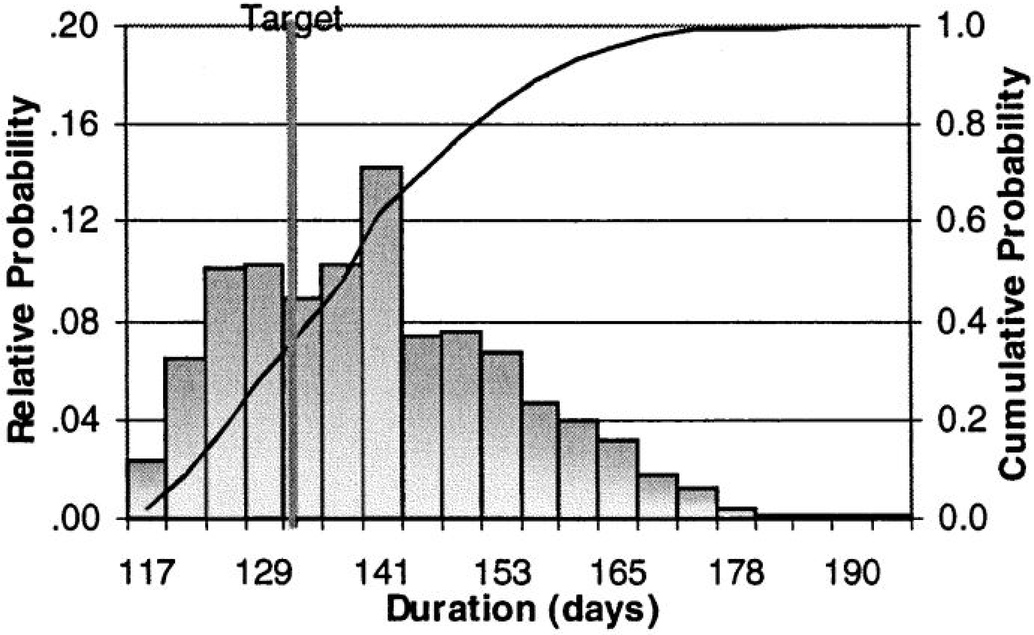
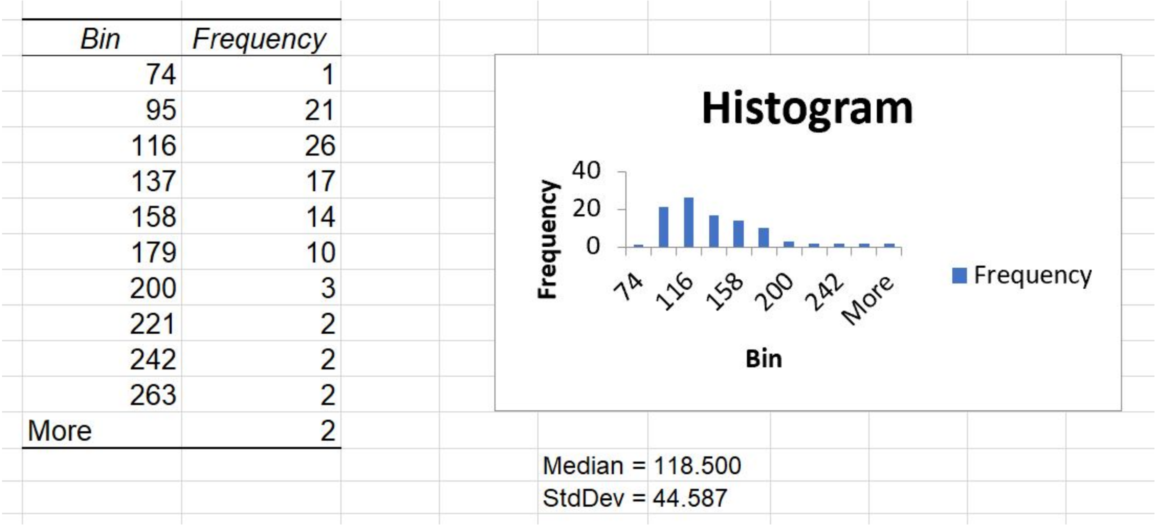


Figure 5-9: UCAV Simulated Duration
Source: Browning and Eppinger, 2002

and cost outcomes for the process. Figure 5-9 shows the distribution of the duration outcome from such a simulation on the UCAV preliminary design process.

## 5.3 The DSM Excel Macro

For this thesis, I will be doing the above analysis and simulation of various theoretical PDPs utilizing an Excel macro originally programmed by Prof. Eppinger's students at MIT that can handle common DSM operations that can be found at *www.dsmweb.org* (Mirshekarian, 2015). The slight differences from the above UCAV example is that I will only be looking at length and not cost of each task since cost is hard to generalize. Additionally, the macro uses the terminology 'learning curve' instead of 'improvement curve', but means numerically the same thing. Figure 5-10 shows an example output of this macro. The bin numbers correspond to a given time interval. That could be days or weeks. For this thesis, I will be normalizing the time intervals, so they will be unit-less. For each bin, the figure shows how many simulations out of 100 had



| *Bin* | *Frequency* |
|---|---|
| 74 | 1 |
| 95 | 21 |
| 116 | 26 |
| 137 | 17 |
| 158 | 14 |
| 179 | 10 |
| 200 | 3 |
| 221 | 2 |
| 242 | 2 |
| 263 | 2 |
| More | 2 |

Median = 118.500
StdDev = 44.587

Figure 5-10: Example DSM Macro Simulation Results

durations greater than the previous bin number and less than or equal to the time indicated by that bin number. The Histogram plots that out. And you can then see the median and standard deviation of this process at the bottom of the figure.

A more thorough explanation of how to use the DSM Excel Macro is presented in Appendix B.

# Chapter 6

# Analysis of a Phase-Gate Product Development Process

This chapter introduces an example Phase-Gate product development process that is representative of one used within automotive. From this example, we delve deeper into the section of the process where requirements and technology features are determined. We briefly present a case from another thesis that exemplifies how the current process can delay technology integration (Sequeira, 1991). The chapter then analyzes the schedule performance of that PDP using DSM simulation to present a baseline for the next chapter.

## 6.1 A representative automotive phase-gate product development process

Figure 6-1 is a simplified presentation of an automaker's current Vehicle Development Process (VDP) as introduced in Chapter 2 with critical milestones marking the end of phases signified by the home plate symbol. The solid sections of the phases represent when that phase is in full swing. The shaded area represents when ancillary tasks related to the phase are being done. This representation is from an actual automaker's handout given to their suppliers to teach them about their current PDP.

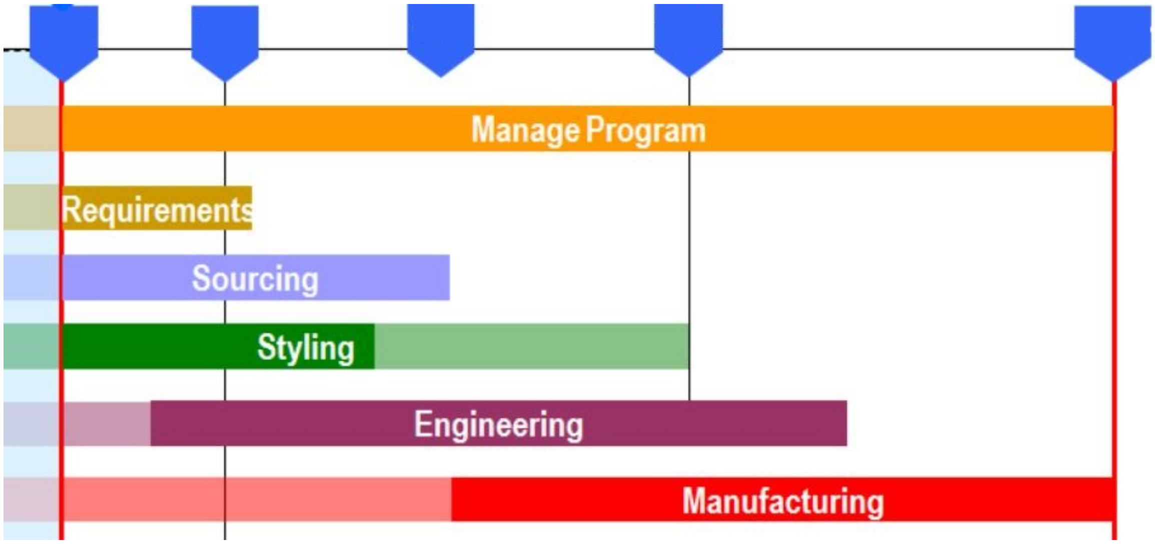


Figure 6-1: Vehicle Development Process with Milestones

Specifics of the current process cannot be published due to proprietary concerns. However, fortunately Sequeira modeled such a process at Chrysler many years ago using a Design Structure Matrix and was given publication permission. See Figure 6-2.

While decades separate the two processes, the similarities are still stark. Concept Development corresponds to the Requirements phase in gold in the VDP milestone chart. Theme Development corresponds to the Styling Phase in green. The Part Development box corresponds to the VDP's Engineering Phase in purple. And finally the combination of the Die, Tooling and Fixture Development boxes corresponds to the Manufacturing phase in red. Note that the area lightly shaded in blue before the first milestone in the VDP chart is meant to represent the planning process around using shared resources between multiple vehicles and thus multiple products. And the Sourcing phase and third milestone are obviously specific to a parallel procurement and supply chain process to identify suppliers for parts.

One large difference between present day and three decades ago is the robustness of virtual design and engineering tools. While automakers still heavily rely on clay models, the ability to design and engineer things virtually has allowed for much greater overlap between the styling and engineering phase as can be seen in the VDP overview.

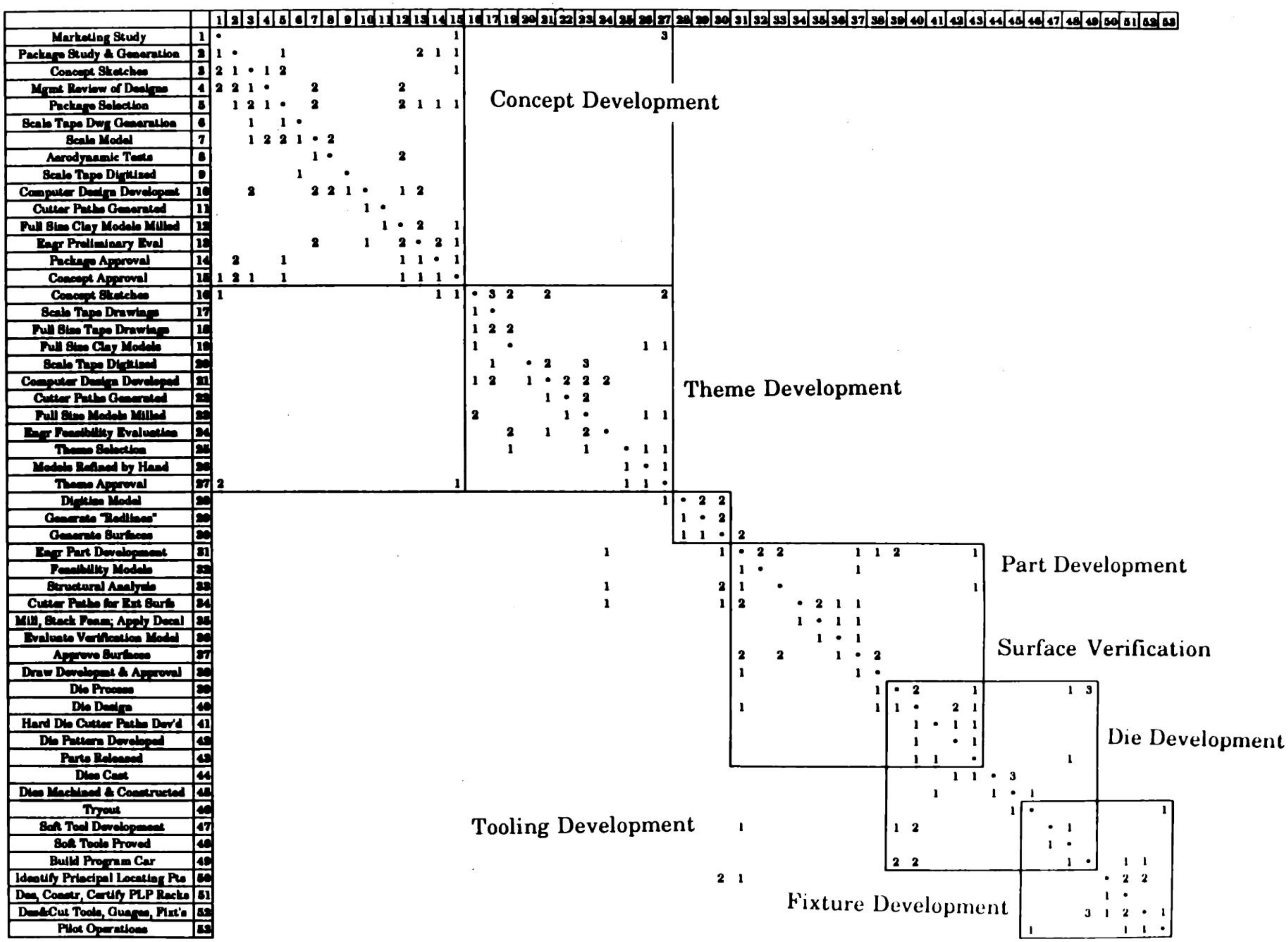


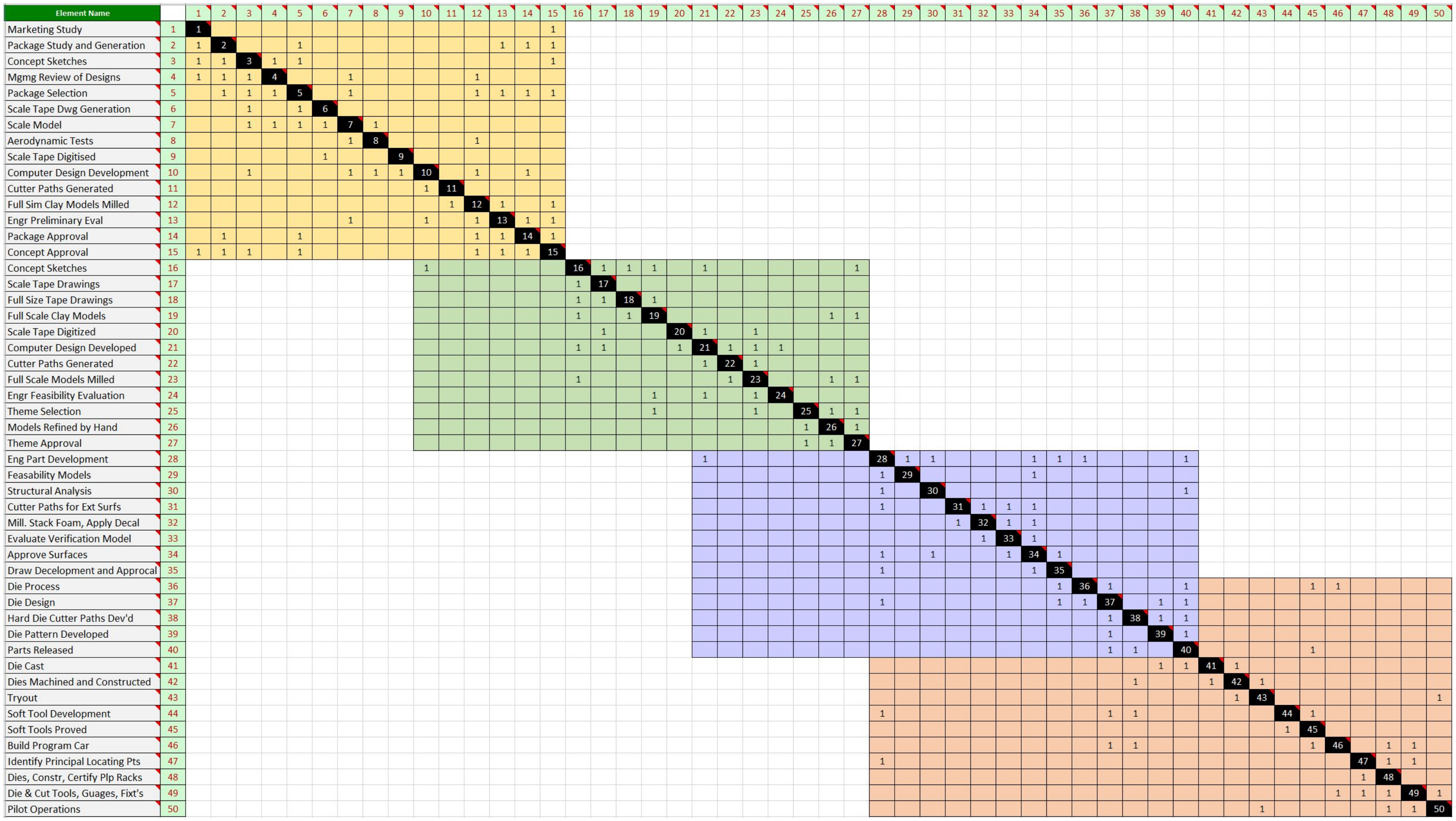
Figure 6-2: Chrysler's PDP in a DSM. Source: Sequeira, 1991

## 6.2 A DSM representation of that process

Based on Sequeira's original DSM, but incorporating more overlap between styling and engineering, I created a DSM to act as a high level model of a vehicle Phase-Gate product development process. See Figure 6-3. I have highlighted the different boxes in the colors corresponding to the respective phases in Figure 6-1: Requirements, Styling, Engineering, and Manufacturing. You can see how the phases have been overlapped a bit more, with Engineering and Manufacturing especially intertwined. Details of this DSM are shared in Appendix Section A.1.

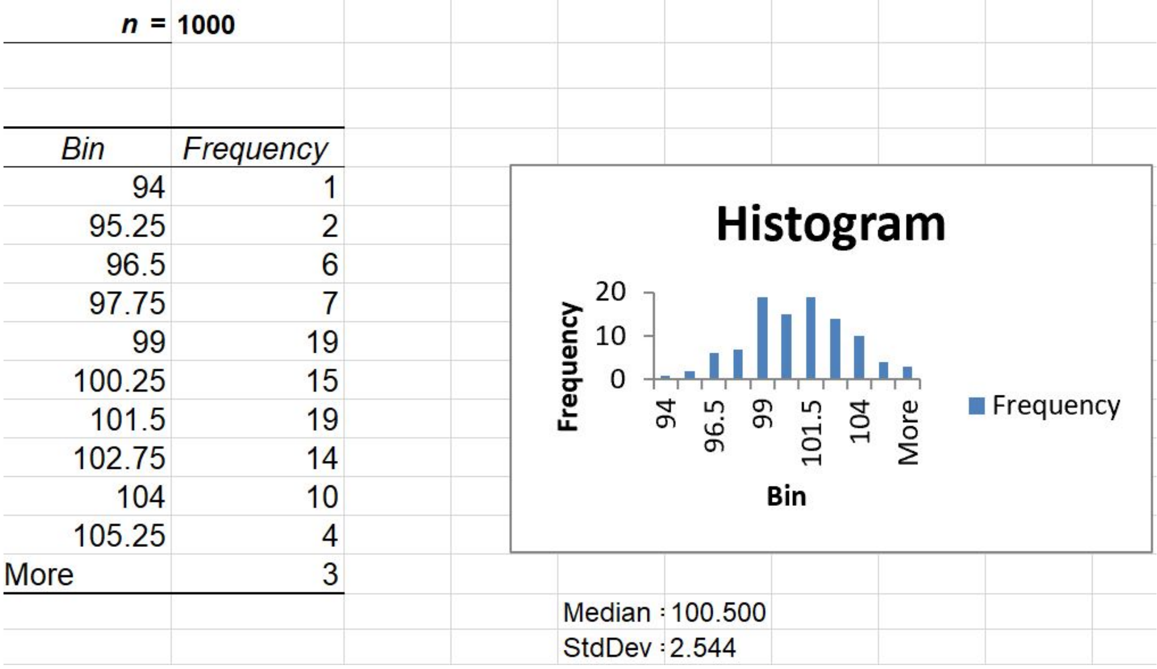
While I have kept some of the process step names, they are not that important for the purposes of this thesis. More important is the process development structure and how the DSM is able to present the way steps within a stage interact with each other and how stages within the overall process interact. While the relative length of each step have some common sense values, they in no means are meant to indicate an empirical value. Critically, the numbers used for length of each step, probability of rework, and impact of rework were ultimately chosen to create a process that took on average of around 100 time units to complete from start to finish with a controlled standard deviation that would be acceptable. This is meant to normalize the model for easy comparison to changes that will be proposed in the following chapter.

With these broad assumptions, running the model Phase-Gate process in the DSM Excel Macro as presented at the end of the previous chapter resulted in a mean time of 100.5 and standard deviation of 2.54 (which would correspond to around 37-46 days for a theoretical 4-5 year process). See Figure 6-4. Note that the macro only plots the first 100 runs in the bins and histogram, but the median and standard deviation values are derived from simulating the process 1000 times.



| Element Name | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 | 1 | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Study and Generation | 2 | 1 | 2 | | | 1 | | | | | | | | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 3 | 1 | 1 | 3 | 1 | 1 | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mgmg Review of Designs | 4 | 1 | 1 | 1 | 4 | | | 1 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Selection | 5 | | 1 | 1 | 1 | 5 | | 1 | | | | | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Dwg Generation | 6 | | | 1 | | 1 | 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Model | 7 | | | 1 | 1 | 1 | 1 | 7 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aerodynamic Tests | 8 | | | | | | | 1 | 8 | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitised | 9 | | | | | | 1 | | | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Development | 10 | | | 1 | | | | 1 | 1 | 1 | 10 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 11 | | | | | | | | | | 1 | 11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Sim Clay Models Milled | 12 | | | | | | | | | | | 1 | 12 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Preliminary Eval | 13 | | | | | | | 1 | | | 1 | | 1 | 13 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Approval | 14 | | 1 | | | 1 | | | | | | | 1 | 1 | 14 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Approval | 15 | 1 | 1 | 1 | | 1 | | | | | | | 1 | 1 | 1 | 15 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 16 | | | | | | | | | | 1 | | | | | | 16 | 1 | 1 | 1 | | 1 | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Drawings | 17 | | | | | | | | | | | | | | | | 1 | 17 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Size Tape Drawings | 18 | | | | | | | | | | | | | | | | 1 | 1 | 18 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Clay Models | 19 | | | | | | | | | | | | | | | | 1 | | 1 | 19 | | | | | | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitized | 20 | | | | | | | | | | | | | | | | | 1 | | | 20 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Developed | 21 | | | | | | | | | | | | | | | | 1 | 1 | | | 1 | 21 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 22 | | | | | | | | | | | | | | | | | | | | | 1 | 22 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Models Milled | 23 | | | | | | | | | | | | | | | | 1 | | | | | | 1 | 23 | | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Feasibility Evaluation | 24 | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | 24 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Selection | 25 | | | | | | | | | | | | | | | | | | | 1 | | | | 1 | | 25 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Models Refined by Hand | 26 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 26 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Approval | 27 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 27 | | | | | | | | | | | | | | | | | | | | | | | |
| Eng Part Development | 28 | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 28 | 1 | 1 | | | | 1 | 1 | 1 | | | | 1 | | | | | | | | | | |
| Feasability Models | 29 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 29 | | | | | 1 | | | | | | | | | | | | | | | | |
| Structural Analysis | 30 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 30 | | | | | | | | | | 1 | | | | | | | | | | |
| Cutter Paths for Ext Surfs | 31 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 31 | 1 | 1 | 1 | | | | | | | | | | | | | | | | |
| Mill. Stack Foam, Apply Decal | 32 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 32 | 1 | 1 | | | | | | | | | | | | | | | | |
| Evaluate Verification Model | 33 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 33 | 1 | | | | | | | | | | | | | | | | |
| Approve Surfaces | 34 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | 1 | 34 | 1 | | | | | | | | | | | | | | | |
| Draw Decelopment and Approcal | 35 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | 1 | 35 | | | | | | | | | | | | | | | |
| Die Process | 36 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 36 | 1 | | | 1 | | | | | 1 | 1 | | | | |
| Die Design | 37 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 1 | 1 | 37 | | 1 | 1 | | | | | | | | | | |
| Hard Die Cutter Paths Dev'd | 38 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 38 | 1 | 1 | | | | | | | | | | |
| Die Pattern Developed | 39 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 39 | 1 | | | | | | | | | | |
| Parts Released | 40 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | 40 | | | | | 1 | | | | | |
| Die Cast | 41 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 41 | 1 | | | | | | | | |
| Dies Machined and Constructed | 42 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 1 | 42 | 1 | | | | | | | |
| Tryout | 43 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 43 | | | | | | | 1 |
| Soft Tool Development | 44 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | 1 | 1 | | | | | | 44 | 1 | | | | | |
| Soft Tools Proved | 45 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 45 | | | | | |
| Build Program Car | 46 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | | | | 1 | 46 | | 1 | 1 | |
| Identify Principal Locating Pts | 47 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | 47 | 1 | 1 | |
| Dies, Constr, Certify Plp Racks | 48 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 48 | | |
| Die & Cut Tools, Guages, Fixt's | 49 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 1 | 49 | 1 |
| Pilot Operations | 50 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | 1 | 1 | 50 |

Figure 6-3: Phase-Gate DSM



*n* = 1000

| *Bin* | *Frequency* |
|---|---|
| 94 | 1 |
| 95.25 | 2 |
| 96.5 | 6 |
| 97.75 | 7 |
| 99 | 19 |
| 100.25 | 15 |
| 101.5 | 19 |
| 102.75 | 14 |
| 104 | 10 |
| 105.25 | 4 |
| More | 3 |

Median : 100.500
StdDev : 2.544

Figure 6-4: Phase-Gate Normalized Simulated Duration

## 6.3 Where requirements and technology feature decisions are made

A critical thing to discuss in a bit more detail is how this Phase-Gate process determines what technology and any new features get incorporated within the vehicle. Because a vehicle is probably the most expensive thing a consumer buys outside of a home, the expectation for coordinated fit and finish are high. What this means though, especially with a Phase-Gate process, is that the final components of the vehicle, to include technological content, is determined early and protected from change later in the process.

Within the context of the PDP model, this means that what technology is included in the final product is determined at the Concept Approval milestone. This ensures the components can be seamlessly incorporated within the Theme, Engineering, and Manufacturing phases. As discussed earlier in this thesis, that translates to technology content decisions being made three or more years prior to launch of the product. With technology moving so quickly and people more inclined to choose a car based on its technological features rather than just engine and styling, this poses a problem for automakers. The current process ensures their product will always have technology that is years behind the current technology market.

## 6.4 A quick case study of a missed opportunity

A contemporary and relevant case study of just this challenge happening at an automaker is presented by Olechowski (2017). Her thesis in general discusses how decisions are made in complex engineering tasks through the modeling of decision trees. And one of her case studies is about an automaker that has to decide on whether to introduce wireless phone charging into a new vehicle.

The problem in the presented case is that when the required decision point came (which was years before launch), the technology was not at a high enough readiness level. Specifically, prototypes had shown the wireless charging module to overheat. Figure 6-6 shows the decision tree the thesis presents. In this scenario, the only options at the time were to go to 'Plan B' (at the top of the tree) of no charger or 'Delay' the entire program in order to incorporate the technology. In the end, based on this decision tree, the delay costs were too much, even with the projected $75M value to the company of launching with this technology. And so the automaker ultimately decided to forego being first to market with a wireless phone charger.

The next chapter will show how additive manufacturing could enable a parallel Agile product development process that could have developed the wireless charger to the necessary readiness, concurrently with the vehicle's main PDP. This would have avoided the $90M delay cost and may have allowed for the vehicle to have been released with the new technology.

Figure 6-5: Example of a car's wireless phone charger
Source: Olechowski, 2017

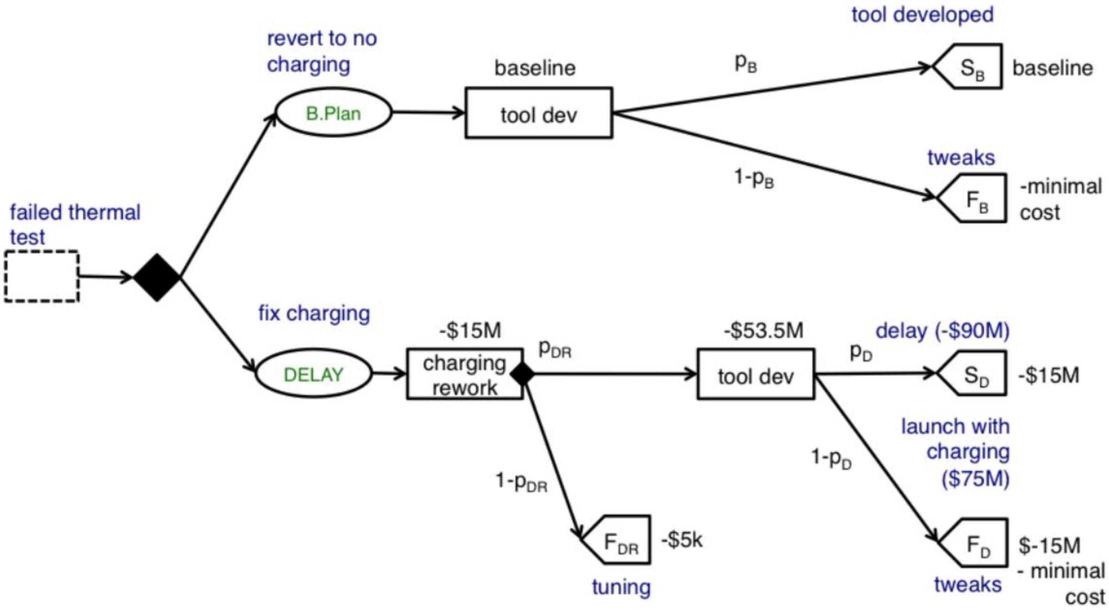


Figure 6-6: Decision tree for major automotive program wireless phone charger
Source: Olechowski, 2017

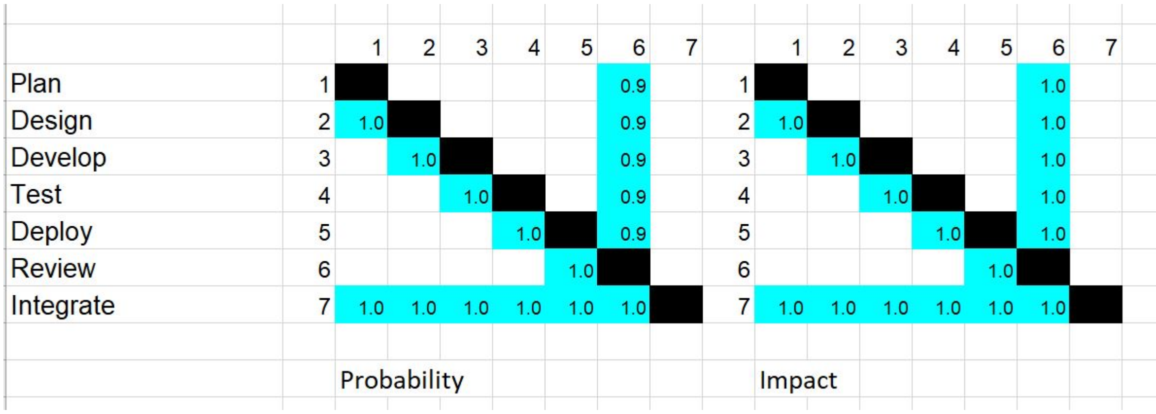
# Chapter 7

# Presenting a Parallel Agile Phase Gate Process

This chapter introduces a DSM of a simple Agile product development process. It then proposes how such an Agile PDP could be run in parallel to and then integrated with a Phase-Gate process. I then discuss why Additive Manufacturing is critical to the success of such a Parallel Agile Phase-Gate Process. I follow that up by putting these Agile iterations into the financial context of Real Options. I use that context to then present a framework that could be used by companies to create a financial decision process on whether to pursue certain development efforts via an AM-enabled Parallel Agile Process. The chapter ends by analyzing Cooper's Hybrid Agile Phase-Gate Process and discusses the advantages of the Parallel process in comparison.

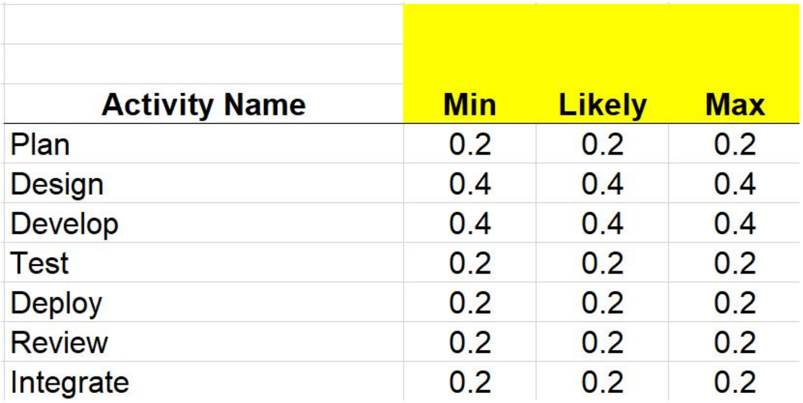
## 7.1 An Agile Design Structure Matrix

As described in Section 2.3, the Agile process is based around completing a series of iterations that deliver a usable end product that can be tested and then improved upon with each iteration. The series of steps that happen during each iteration are often labeled as Plan, Design, Develop, Test, Deploy, Review, Launch. Figure 7-1 is the Probability and Impact DSM matrices that show this process with Integrate replacing the Launch step for the purposes of better describing what would happen



| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plan | 1 | ■ | | | | | 0.9 | | 1 | ■ | | | | | 1.0 | |
| Design | 2 | 1.0 | ■ | | | | 0.9 | | 2 | 1.0 | ■ | | | | 1.0 | |
| Develop | 3 | | 1.0 | ■ | | | 0.9 | | 3 | | 1.0 | ■ | | | 1.0 | |
| Test | 4 | | | 1.0 | ■ | | 0.9 | | 4 | | | 1.0 | ■ | | 1.0 | |
| Deploy | 5 | | | | 1.0 | ■ | 0.9 | | 5 | | | | 1.0 | ■ | 1.0 | |
| Review | 6 | | | | | 1.0 | ■ | | 6 | | | | | 1.0 | ■ | |
| Integrate | 7 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | ■ | 7 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | ■ |
| | | Probability | | | | | | | | Impact | | | | | | |

Figure 7-1: A Generic Agile Process in DSM Form

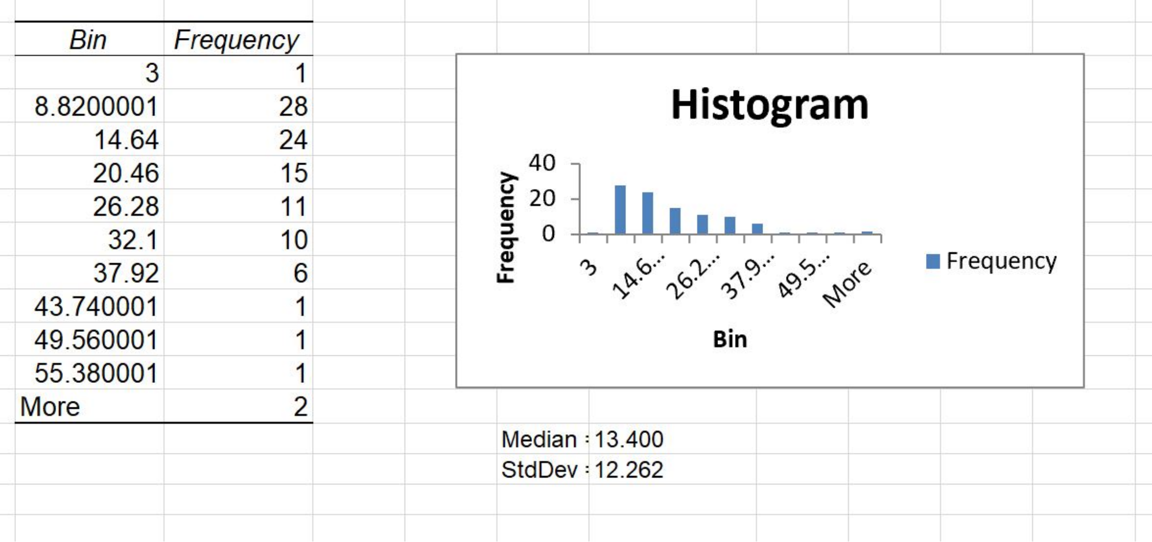


| Activity Name | Min | Likely | Max |
|---|---|---|---|
| Plan | 0.2 | 0.2 | 0.2 |
| Design | 0.4 | 0.4 | 0.4 |
| Develop | 0.4 | 0.4 | 0.4 |
| Test | 0.2 | 0.2 | 0.2 |
| Deploy | 0.2 | 0.2 | 0.2 |
| Review | 0.2 | 0.2 | 0.2 |
| Integrate | 0.2 | 0.2 | 0.2 |

Figure 7-2: Agile Process Step Lengths

during this step when combining it with a larger Phase-Gate process. I am introducing this DSM representation of an Agile process, because I will integrate this process into the Phase-Gate DSM as presented in the previous chapter.

As you can see, when the Review step comes up, there is a 90% probability that the output of this step will require the five previous steps, as denoted with *0.9* entries in Column 6, to be repeated. This follows the IR (input in row/output in column) convention as described in Section 5.1. Thus, there is a very high chance that a new iteration will need to be started after the Review step. We are assuming this probability is constant for each successive pass as a way to model the *progressive iterative* nature of an Agile process. One could argue that the probability should decrease after each pass. However, it is also true with iterative development that sometimes you get closer to your solution, but sometimes you find more problems and



| Bin | Frequency |
|---|---|
| 3 | 1 |
| 8.8200001 | 28 |
| 14.64 | 24 |
| 20.46 | 15 |
| 26.28 | 11 |
| 32.1 | 10 |
| 37.92 | 6 |
| 43.740001 | 1 |
| 49.560001 | 1 |
| 55.380001 | 1 |
| More | 2 |

Median : 13.400
StdDev : 12.262

Figure 7-3: Agile Simulated Duration

more work after each iteration. In the end, the constant 90% probability of rework gives us an appropriate simulated duration that has a high standard of deviation. Also note that the impact matrix shows that the repeated steps have to be fully reworked. This is due to the fact that many implementations of Agile (e.g. Scrum) are based on set time efforts and so each iteration takes the full amount of time. Finally, it is not until all six steps before Integrate are satisfactorily completed can we exit the Agile process.

Figure 7-2 shows the process step assumptions with numbers that were chosen to be proportionate to the activity values of the normalized Phase-Gate PDP presented in Section 6.2. The minimum, likely, and maximum times are the same due to the strict time bounding of a Sprint within most Agile processes. Adding up the times from Plan to Review comes to 1.6, which can be interpreted as that each sprint taking up 1.6% of how long the overall project is expected to take. This would correspond to a Sprint taking from 2.5 to 4 weeks within a 3 to 5 year PDP. That corresponds to a Sprint time that is reasonable for our analysis. Figure 7-3 shows the results of this DSM being simulated. The Median of 13.4 shows that most simulations required around 8 Sprints to complete. As expected, the standard deviation of this modeled Agile process is large.

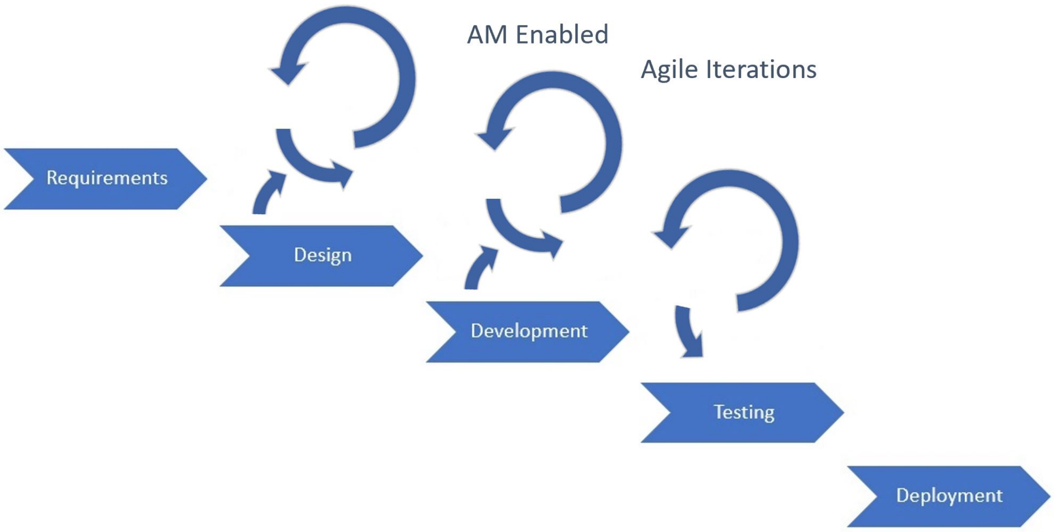


Figure 7-4: A Phase Gate Process with parallel agile iterations that complete a 'Design, Develop, Test, Deploy, Review' cycle multiple times while incorporating feedback from the phase gate process to ensure seamless integration into product closer to launch

## 7.2 Integrating the Agile DSM

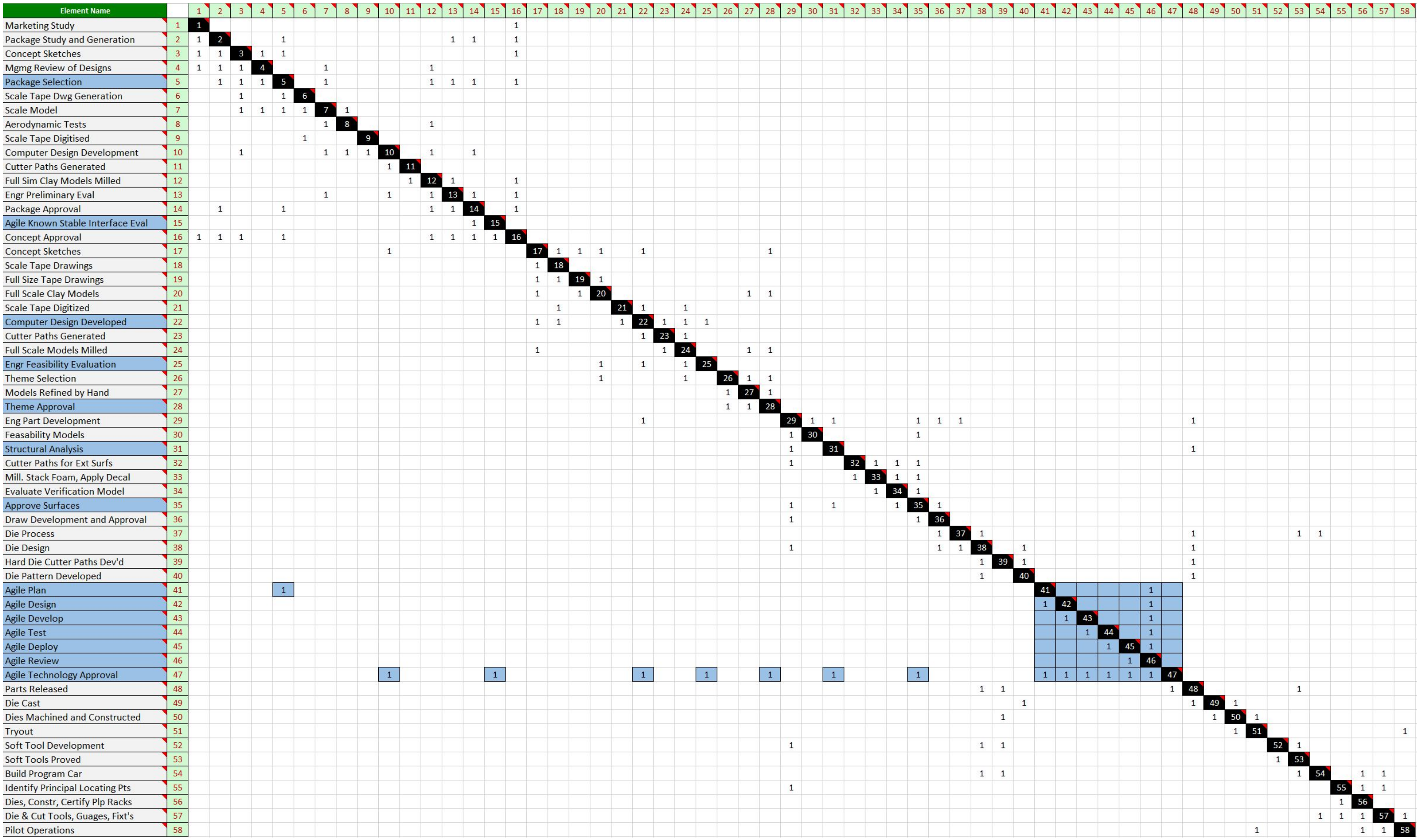
Based on the discussion in section 6.3, having to commit to the technology content of a product by the requirements or concept approval step when your PDP is multi-years in length causes you to make undesired compromises. What if instead of being limited to a Phase-Gate process for new technology, you could in parallel run an Agile process that could get newer technologies mature enough for integration into the rest of your product?

I argue with some pre-planning in the form of creating known stable interfaces, you can do that with limited cost to your overall schedule. If at the Concept Approval step, a technology was not quite ready, similar to the wireless charger and its overheating issue, you could execute designing and engineering for a Plan A and a Plan B. Plan B would be to go to production without the improved technology. That would entail following the traditional Phase-Gate plan with decisions made early and risks minimized. However, Plan A would include devoting resources to iterating on improving the new technology via an Agile process. You would design a known stable interface that both Plan B and Plan A would be able to hook into the product. Figure 7-4 depicts such a process. And Figure 7-5 depicts a DSM that shows how the previously introduced Agile process (highlighted in blue in the DSM) would integrate into the Phase Gate model from the previous chapter.

The Package Selection step where the contents of the vehicle are determined kicks off the parallel Agile process for components of the vehicle that are desired but not at the needed technology readiness level. An extra step is added that requires designing those known stable interfaces. And as the rest of the PDP continues, the Agile Process iterates multiple times in parallel. Note that the Agile process is continuously being fed info from the main PDP (note the highlighted elements and corresponding individual blue cells below the diagonal) into the integration step. This is important since the agile process needs to be updated with any new information to ensure the outcome of the parallel process is ready for seamless integration by Part Release (the step where all parts are finalized to their ultimate specifications).

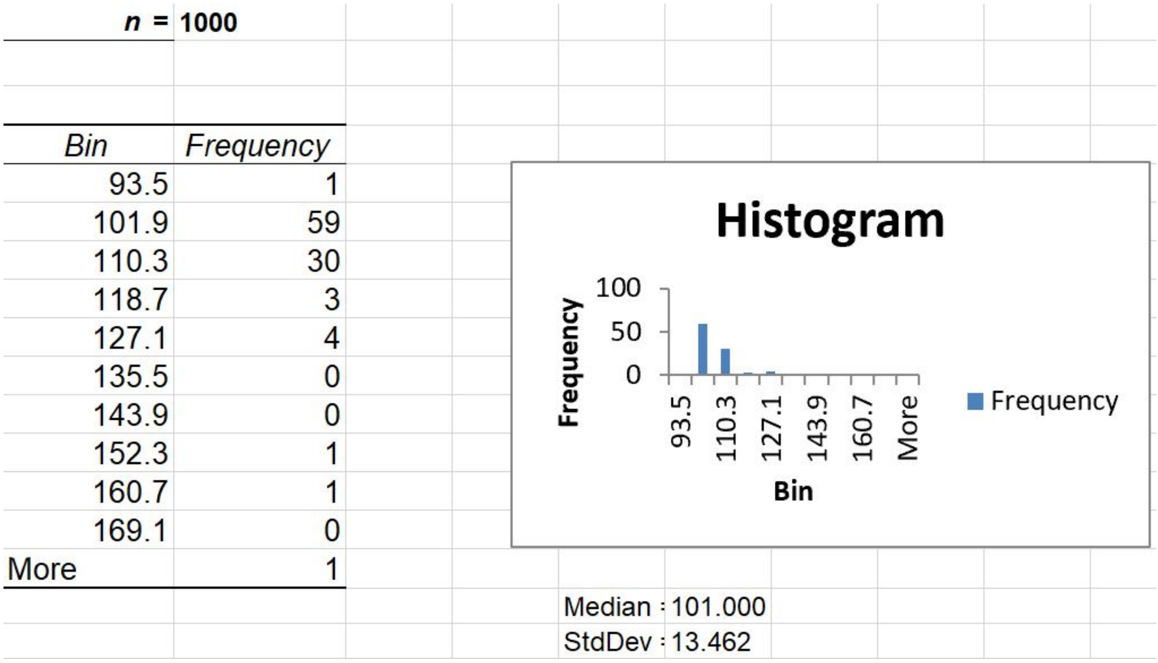
As can be seen in Figure 7-6, the mean time is almost identical, while the standard deviation is predictably higher. We see that in 60% of the simulations, the Agile process converged to a solution in time for the Parts Release step and there was little to no schedule overrun. These are the 60 instances in *Bin 101.9* or lower. This meant the new technology could have been integrated into the vehicle without any schedule costs. For the remaining 40% of simulations, the Agile process did not converge to a solution by the Parts Release step and if continued, there would have been schedule a overrun. These are the 40 instances in *Bin 110.3* or higher. The details of the DSM analysis can be found in Appendix A.2.

Instead of accepting that overrun, the project manager would have decided to go forward with the traditional Plan B solution. Even though 75% of those overruns amounted to less than a 10% schedule slip (the 30 instances in *Bin 110.3*), for complex hardware projects with high launch and marketing investments, any schedule slip could be prohibitively expensive. The program would instead decide to move forward without the new technology.



| Element Name | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 | 1 | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Study and Generation | 2 | 1 | 2 | | | 1 | | | | | | | | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 3 | 1 | 1 | 3 | 1 | 1 | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mgmg Review of Designs | 4 | 1 | 1 | 1 | 4 | | | 1 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Selection | 5 | | 1 | 1 | 1 | 5 | | 1 | | | | | 1 | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Dwg Generation | 6 | | | 1 | | 1 | 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Model | 7 | | | 1 | 1 | 1 | 1 | 7 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aerodynamic Tests | 8 | | | | | | | 1 | 8 | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitised | 9 | | | | | | 1 | | | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Development | 10 | | | 1 | | | | 1 | 1 | 1 | 10 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 11 | | | | | | | | | | 1 | 11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Sim Clay Models Milled | 12 | | | | | | | | | | | 1 | 12 | 1 | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Preliminary Eval | 13 | | | | | | | 1 | | | 1 | | 1 | 13 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Approval | 14 | | 1 | | | 1 | | | | | | | 1 | 1 | 14 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agile Known Stable Interface Eval | 15 | | | | | | | | | | | | | | 1 | 15 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Approval | 16 | 1 | 1 | 1 | | 1 | | | | | | | 1 | 1 | 1 | 1 | 16 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 17 | | | | | | | | | | 1 | | | | | | | 17 | 1 | 1 | 1 | | 1 | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Drawings | 18 | | | | | | | | | | | | | | | | | 1 | 18 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Size Tape Drawings | 19 | | | | | | | | | | | | | | | | | 1 | 1 | 19 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Clay Models | 20 | | | | | | | | | | | | | | | | | 1 | | 1 | 20 | | | | | | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitized | 21 | | | | | | | | | | | | | | | | | | 1 | | | 21 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Developed | 22 | | | | | | | | | | | | | | | | | 1 | 1 | | | 1 | 22 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 23 | | | | | | | | | | | | | | | | | | | | | | 1 | 23 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Models Milled | 24 | | | | | | | | | | | | | | | | | 1 | | | | | | 1 | 24 | | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Feasibility Evaluation | 25 | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | 25 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Selection | 26 | | | | | | | | | | | | | | | | | | | | 1 | | | | 1 | | 26 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Models Refined by Hand | 27 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 27 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Approval | 28 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 28 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eng Part Development | 29 | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 29 | 1 | 1 | | | | 1 | 1 | 1 | | | | | | | | | | | 1 | | | | | | | | | | |
| Feasability Models | 30 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 30 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Structural Analysis | 31 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 31 | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | |
| Cutter Paths for Ext Surfs | 32 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 32 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Mill. Stack Foam, Apply Decal | 33 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 33 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Evaluate Verification Model | 34 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 34 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Approve Surfaces | 35 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | 1 | 35 | 1 | | | | | | | | | | | | | | | | | | | | | | |
| Draw Development and Approval | 36 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | 1 | 36 | | | | | | | | | | | | | | | | | | | | | | |
| Die Process | 37 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 37 | 1 | | | | | | | | | | 1 | | | | | 1 | 1 | | | | |
| Die Design | 38 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 1 | 1 | 38 | | 1 | | | | | | | | 1 | | | | | | | | | | |
| Hard Die Cutter Paths Dev'd | 39 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 39 | 1 | | | | | | | | 1 | | | | | | | | | | |
| Die Pattern Developed | 40 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 40 | | | | | | | | 1 | | | | | | | | | | |
| Agile Plan | 41 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 41 | | | | | 1 | | | | | | | | | | | | |
| Agile Design | 42 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 42 | | | | 1 | | | | | | | | | | | | |
| Agile Develop | 43 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 43 | | | 1 | | | | | | | | | | | | |
| Agile Test | 44 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 44 | | 1 | | | | | | | | | | | | |
| Agile Deploy | 45 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 45 | 1 | | | | | | | | | | | | |
| Agile Review | 46 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 46 | | | | | | | | | | | | |
| Agile Technology Approval | 47 | | | | | | | | | | 1 | | | | | 1 | | | | | | | 1 | | | 1 | | | 1 | | | 1 | | | | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 47 | | | | | | | | | | | |
| Parts Released | 48 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | | | | | 1 | 48 | | | | | 1 | | | | | |
| Die Cast | 49 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | 1 | 49 | 1 | | | | | | | | |
| Dies Machined and Constructed | 50 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | 1 | 50 | 1 | | | | | | | |
| Tryout | 51 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 51 | | | | | | | 1 |
| Soft Tool Development | 52 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | 1 | 1 | | | | | | | | | | | | | 52 | 1 | | | | | |
| Soft Tools Proved | 53 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 53 | | | | | |
| Build Program Car | 54 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | | | | | | | | | | | 1 | 54 | | 1 | 1 | |
| Identify Principal Locating Pts | 55 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 55 | 1 | 1 | |
| Dies, Constr, Certify Plp Racks | 56 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 56 | | |
| Die & Cut Tools, Guages, Fixt's | 57 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 1 | 57 | 1 |
| Pilot Operations | 58 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | 1 | 1 | 58 |

Figure 7-5: Parallel Agile-Phase-Gate DSM



*n* = 1000

| *Bin* | *Frequency* |
|---|---|
| 93.5 | 1 |
| 101.9 | 59 |
| 110.3 | 30 |
| 118.7 | 3 |
| 127.1 | 4 |
| 135.5 | 0 |
| 143.9 | 0 |
| 152.3 | 1 |
| 160.7 | 1 |
| 169.1 | 0 |
| More | 1 |

Median : 101.000
StdDev : 13.462

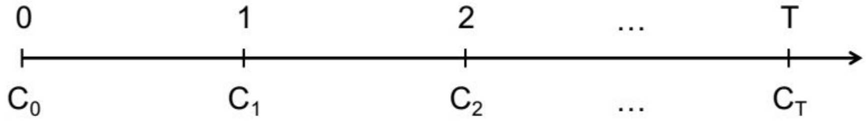
Figure 7-6: Simulation Results of a Parallel Agile-Phase Gate PDP

The big difference between this method and what was discussed previously in Section 6.4 with the wireless charger is that this decision is now substantially closer to market launch. You gave the new technology a fighting chance to be integrated and that would give your company a competitive edge in the market. A framework for making such financial decisions is discussed in the following section.

## 7.3 Parallel Agile Development described in Financial Terms - Real Options

Obviously, a parallel development process would not be free. However, by simply looking at this in Real Option terms, you could determine whether pursuing certain efforts would be worth it. Below is the basic formula for how to value a project in *Net Present Value* (NPV) terms with Real Options. Net Present Value is a basic financial term for the value of a project based on expected cash flows (both income and expenditures) adjusted for time (inflation and opportunity costs) (Verner, 2019).

Suppose a project has the following cash flows:



The value of this project is its $NPV$ with $r$ being a discount rate that accounts for inflation and opportunity costs so you can do a fair comparison. Money today is worth more than money next year.

$$NPV = C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_T}{(1+r)^T}$$

The decision rule is thus to do the project if the NPV $>$ 0, because 'it creates value.' However, many projects have 'embedded real options' allowing you to make additional choices in the future. One example is the *Abandonment Option* which allows you to shut down an effort if it is going badly. Such options are clearly valuable and should be accounted for in the valuation of a project. So:

NPV(project) = NPV(w/o real options) + Value of real options

Source: Verner, 2019

To value the option of pursuing a parallel product development process, you would have to make educated estimates of three things:

1. Expected value to the project if that new technology is successfully integrated.

2. Expected development costs.

3. Estimated chance of developing the technology by Parts Release.

For the first item, marketing teams are very adept at valuing features in terms of profit, especially if this is a feature or option you are charging extra for. What might be harder is determining the value to the brand of getting to market early with this feature. For development costs, engineering teams would also be able to come up with some type of estimation, especially if they are time-box constrained. They would need to know how big the team they would be given and how much each workable prototype would cost to produce at the end of each sprint. The last one is more of an art, but these type of estimations are a part of any product development process.

We can use the Wireless Phone Charger Case from Section 6.4 in combination with the example DSM numbers from the previous section to see how you could use this simple principle of option valuing to make a decision of whether to pursue a parallel development effort. For the wireless phone charger, the finance department anticipated a first-year volume for the wireless charging model of 500,000 units, with a manufacturer's suggested retail price increase of $150 based on marketing clinic data. The material cost of the technology was estimated to be $107, leaving a $43 per car profit. Extrapolating that to the full multi-year run of the vehicle, they calculated the increased revenue would total $75M in NPV. Note that this value did not include the possibly large brand-enhancing value of being first to market (Olechowski, 2017, p. 107). As for the probability that the theoretical Agile process would find a solution by Parts Release, I am using the 60% chance from the previous section for argument's sake (see Figure 7-6 where 60 of 100 simulations as graphed out in the histogram complete within 101.9 time units or sooner).

1. Expected value of Wireless Phone charger: $75M
2. Expected development costs (EDC) = To be solved
3. Estimated chance of developing the technology by Parts Release = 60%

Value of Option = $75M x 0.60 - EDC = $45M - EDC

EDC must be < $45M for Value of Option to be > $0

This would lead a company to the decision that as long as the development costs were less than $45M, this would be a worthwhile effort. To ballpark further numbers here, suppose we dedicate a team of 10 engineers that each cost the company including benefits \$200k/year and then provide the team a large \$1M/year hardware budget; this would only cost the company \$3M/year. With the time-constraints of needing to be done by Parts Release, then the team could work on this for at most a couple years. Hence, if the probability of success was truly on the order of 0.60, pursuing this would be an easy decision. As mentioned, this is even without accounting for monetary benefits derived from an increase in brand value by being first to market.

The reason the math works out now when it did not before, is because there is no longer a delay in launch of the vehicle. A delay in launch of the vehicle in the Wireless Phone Charger example was calculated to be about \$1M per day by that automotive company. With a parallel process, you retain the Real Option value to no longer pursue an effort that is not worth it. You have the option to cut your losses before substantial delays to launch happen and that abandonment option has a corresponding substantial value.

Note that the 60% percent chance of success was just used as an example to show the value of the option. Additionally, it was the chance of success estimated at the start of the process. In practice, after each sprint, you could dynamically update the chances of success based on progress and time to Parts Release. As your uncertainty grew less after each iteration, the ability to make a sound financial decision becomes greater. And the relatively quick speed of these iterations means you have more opportunities to re-evaluate and make the right call.

While I presented only a theoretical example to show how such review decisions could be made with the right data, Section 8.4 briefly discusses some future studies that could be done to help project managers have the right data to make these real option decisions.

## 7.4 How Additive Manufacturing is critical to implementation

So why is this not widespread through industry yet? My argument is that this type of parallel, rapid hardware development that can feasibly integrate later into a process, without going through all the same gates as the rest of the product, is only now feasible because of recent improvements to additive manufacturing.

Additive manufacturing now allows a company to make testable prototypes that are near identical in design to the finished component at the speed of Agile sprints. It also allows the parallel agile sprints to incorporate any theme and engineering decisions that are being made in the main Phase-Gate process, no matter how small with little added cost. Without additive manufacturing, it would be too costly to constantly make small changes to prototype tooling as information trickled in from the parallel Phase-Gate process. That would inherently mean that the parallel Agile process would slowly diverge from the main product development and the component would require extensive coordination rework to integrate into the final product. This would inevitably delay the product's release, and the risk would still exist that the integration could ultimately prove impossible.

Current trends to virtualize more development is appropriate in the early design and engineering stages. But physical development is still required, especially for new, untested technology. The example of the overheating wireless car charger in section 6.4 would have clearly required workable prototypes to ensure the unit would not overheat. And if you are dealing with autonomous technology, real world testing would be required by a matter of regulation. When you are creating something innovative and new and not just a step-wise evolution of something in the physical world, physical iteration is almost a requirement. Additive manufacturing allows for those physical iterations to adapt and change to each Agile cycle's learnings at minimal cost. It also allows the development team to create end-use quality components at the end of each sprint, ensuring the new technology is ready to be integrated into the final product with minimal rework.

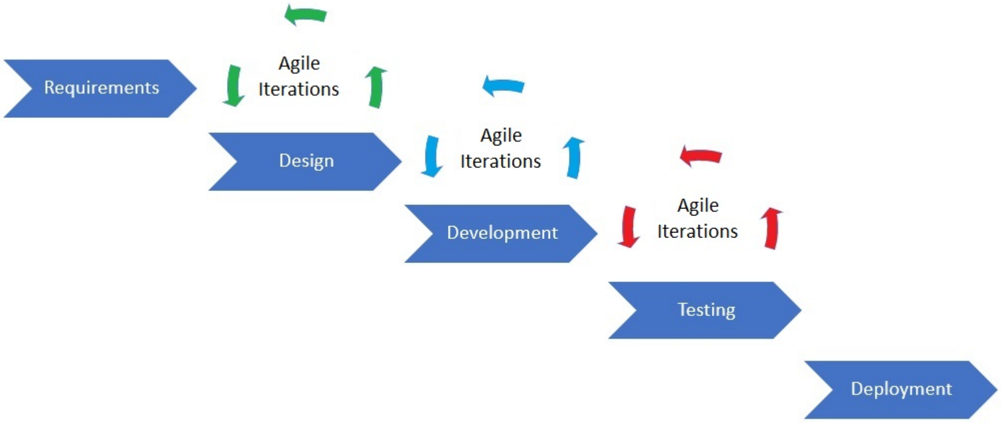


Figure 7-7: Cooper's Hybrid Agile Phase Gate Process where agile development stays within individual gates

## 7.5 Comparing to Cooper's Hybrid Agile Phase Gate Solution

A process worth modeling and comparing to is Cooper's Hybrid Agile-Phase-Gate process as introduced in Section 3.3 (Cooper and Sommer, 2018). As discussed, in many respects with computer aided design and engineering software, iterations are happening within each of the phases. While those iterations are desirable and should be encouraged, the process is still constrained by the rigidity and timing of the Phase-Gate milestones. See Figure 7-7 for a depiction of this. Modeling the Agile process as one that spans multiple gates compared to modeling multiple ones that exist within individual gates might be a nuance. However, I believe it is an important nuance.

Figure 7-8 depicts a DSM of Cooper's process modeled if we were to keep the same characteristics of the Agile process we proposed previously. Note that there are now three separate Agile processes, one each during Concept, Theme and Engineering and they all kick off at or around the approval step of the previous stage.

From Figure 7-9, you can see that having three non-connected iterations causes large overrun with a much higher standard deviation. The data that went into these simulations can be found in Appendix A.3. This obviously would not be feasible.

| Element Name | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 |
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| Marketing Study | 1 |1| | | | | | | | | | | | | | | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Study and Generation | 2 |1|2| | |1| | | | | | | |1|1| | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 3 |1|1|3|1|1| | | | | | | | | | | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mgmg Review of Designs | 4 |1|1|1|4| | |1| | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Selection | 5 | |1|1|1|5| |1| | | | |1|1|1| | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Dwg Generation | 6 | | |1| |1|6| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Model | 7 | | |1|1|1|1|7|1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aerodynamic Tests | 8 | | | | | | |1|8| | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitised | 9 | | | | | |1| | |9| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Development | 10 | | |1| | | |1|1|1|10| |1| |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 11 | | | | | | | | | |1|11| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Sim Clay Models Milled | 12 | | | | | | | | | | |1|12|1| | | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Preliminary Eval | 13 | | | | | | |1| | |1| |1|13|1| | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Approval | 14 | |1| | |1| | | | | | |1|1|14| | | | | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agile Concept Plan | 15 | | | | |1| | | | | | | | | |15| | | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agile Concept Design | 16 | | | | | | | | | | | | | | |1|16| | | |1| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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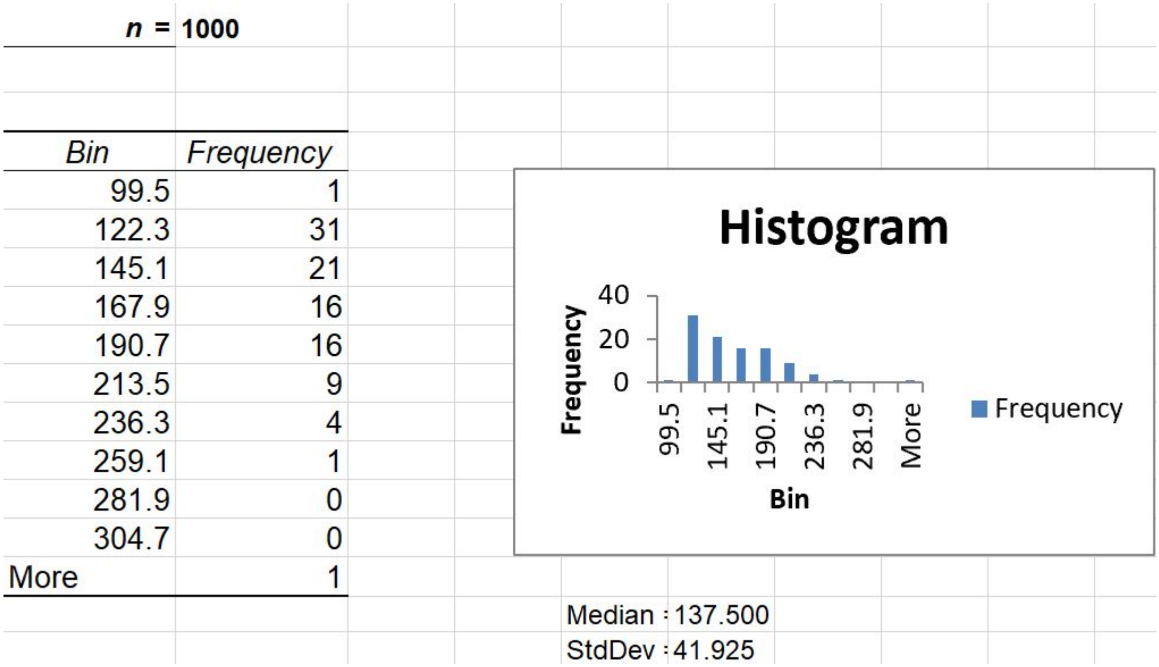
Figure 7-8: Cooper Hybrid Agile-Phase-Gate DSM



*n* = 1000

| *Bin* | *Frequency* |
|---|---|
| 99.5 | 1 |
| 122.3 | 31 |
| 145.1 | 21 |
| 167.9 | 16 |
| 190.7 | 16 |
| 213.5 | 9 |
| 236.3 | 4 |
| 259.1 | 1 |
| 281.9 | 0 |
| 304.7 | 0 |
| More | 1 |

Median : 137.500
StdDev : 41.925

Figure 7-9: Simulation Results of Cooper's Hybrid Agile-Phase Gate PDP

As mentioned in Section 3.3, each stage in this process now takes the longer of the corresponding Phase-Gate or Agile PDP. So in order to make a system like this feasible, you would have to modify the Agile process in such a way as to make it quicker and/or have less iterations. In the DSM model, this could be accomplished by changing the expected time of each step, the probability of rework, or limit the inputs into the Agile process. A major thing to take away from these required modifications is that this Hybrid Agile process, as compared to the one proposed in the previous section, would have less iterations and/or less scope to those iterations. As presented in Chapter 4, less iteration means less likelihood of finding novel solutions or refining to the best solution. In the end, with this PDP architecture, you are handcuffing the flexibility and advantages of Agile unnecessarily.

# Chapter 8

# Discussion

For small embedded systems, realizing a hardware PDP that is fully Agile is possible. However, as shown in the automotive example, there are many larger projects where the controls, manufacturing lead times and capital expenditures still demand a Phase-Gate process. My goal with this thesis was to show how you could design a PDP that could have the advantages of both processes architectures, applying each type dependent on the specific needs of the individual components. Running Agile sprints on a car's frame does not make economic sense, but being able to do so on the increasing number of technology systems integrated into an automobile does.

## 8.1 Key application of this PDP within autonomous

Where I believe this is most critical within automotive is in the development of autonomous vehicles. Within an autonomous project, it is the new, quickly evolving technology that is at the center of the product's value. Deploying years-old technology is not feasible when launching an autonomous offering. However, the underpinnings or chassis of the vehicle do not move at that same speed, and they have the same tooling and capital limitations of a traditional vehicle. The core of the Chrysler Pacifica being used by Waymo, the Chevy Bolt by Cruise, and the Ford Fusion by Argo still follow the same 3-5 year product development cycle they always have. So how are autonomous companies integrating their state-of-the-art components to these

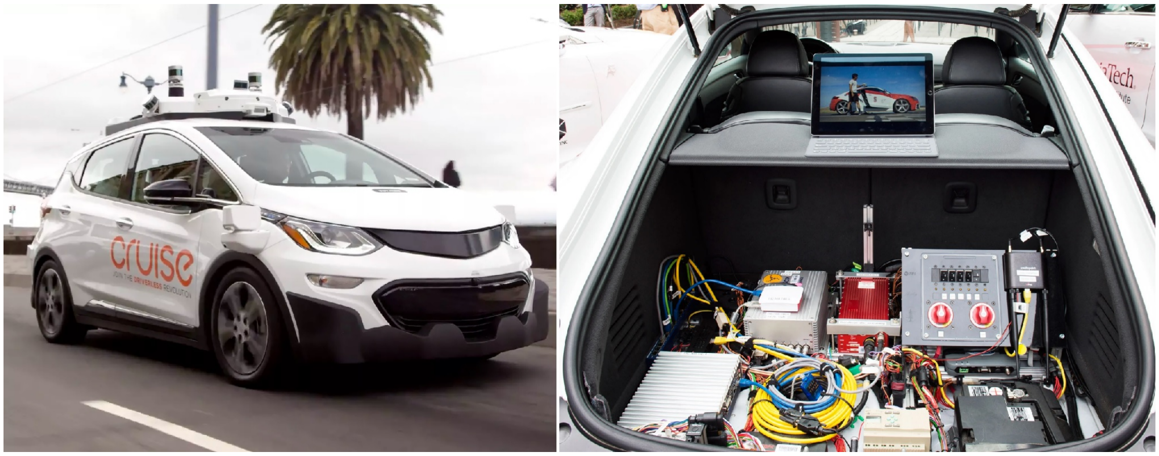


Figure 8-1: An autonomous crown on a GM Cruise and a trunk on a Stanford Univ Audi AV with an autonomous compute stack

Source: GM and Nikki Kahn via Getty Images

vehicles? The current solution is setting all the sensors on a crown or bracket attached to the car.

The development process of the autonomous technology and the underlying automobile are thus completely separated. However, that creates a very inelegant product, with bolted on sensors and computers and cables stuffed into the trunk (see Figure 8-1). The future of autonomous is clearly not going to look like this. The company that can more seamlessly integrate the autonomous technology components into the vehicle will have a very large comparative advantage. The Parallel Agile Phase-Gate Process proposed in this thesis could enable a mobility company to do just that.

## 8.2 Applications of this PDP outside of automotive

An obvious application of this process that has been mentioned a couple times is aviation. Aviation has similar if not more extreme restraints to their product development process. The overall project takes years, yet technology is also at the core of their offering. Current practices within aerospace is to continuously update and bolt on new things to existing airframes. This is because airframe development takes so long and is so expensive. However, the 737 Max is a stark example of how non-integrated product development can have disastrous results. As CAD and CAE become more robust and are able to take on more complex fluid flows, it is likely that airframe refreshes will be more feasible. However, they still will not move at the speed of software or embedded systems like avionics. And with the strict regulations within aviation, the industry will most likely not move away from a Phase-Gate processes. A way to thus integrate Agile development and Phase-Gate within aviation is critical.

With Industry 4.0 upon us and the increasing prevalence of the internet of things, the applications of this process will just continue to grow. Smart cities and smart infrastructure will require the latest technology upon deployment. Creating an express way or a bridge via a completely Agile process is neither quite feasible nor smart. However, being able to integrate the newest connected technologies closer to completion of infrastructure projects will be necessary.

## 8.3 The greater impact of Additive Manufacturing and Digital Fabrication on complex systems: Max customization, a virtual supply chain, and post-deployment hardware updates

Additive manufacturing presents a completely new way to create physical objects. It logically means that this would enable a new type of development process for those products. But AM and digital fabrication in general present many more interesting opportunities, just a couple of which will be briefly introduced here.

The first one, which is already being explored, is the ability for max customization. If you develop the part through additive manufacturing and the final prototype is of finished quality, you could allow customers to make non-functional changes to the part based on their preferences. Mini Cooper is already doing this with dashboard inserts.

Another secondary impact of using additive manufacturing during product development is the ability to then create replacement parts via AM. Khajavi et al. (2018)

discuss this benefit within a military context. However, this virtual supply chain for service parts is becoming a hotter topic within research and industry in general. As mentioned multiple times, launches within automotive and any mass-produced product almost always require traditional tooling for economies of scale. Service parts, on the other hand, are often needed at numbers where AM makes sense. Especially towards the end of a product's life cycle, the ability to accurately forecast need become harder and the holding cost of such inventory is an undesirable cost. If the tooling for the part has been disassembled or lost, the cost of starting up a line can be prohibitive. AM, on the other hand, creates a virtual supply chain of such parts where those parts could be produced as needed.

Finally, AM could provide the ability to do post deployment updates to hardware. Companies like Tesla have popularized the over-the-air software updates which can keep a product fresh years after purchase. Being able to develop and deploy hardware updates to select customers that would be willing to pay for them becomes profitable at smaller scales through AM. If the update is going to the entire product population, traditional manufacturing techniques would likely make more sense. However, the creation of the known stable interface as part of the original product development process makes niche updates much more feasible.

## 8.4 Obligatory Future Work section

By nature of this being a Master's thesis, more work can always be done. Ideally a complex product would be attempted to be created through this or a similar process, helping validate and more likely improve on what is proposed here. This thesis looked mostly at presenting a theoretical process and showing the schedule feasibility of this type of Agile integration. A useful next step would be to study the data from hardware components in industry that have been developed via Agile processes and build a tool set that could be used to help predict the likelihood of that development being successful and how many sprints might be required. This type of data would make the Real Option valuing briefly introduced in Section 7.3 more accurate and useful to a project manager.

Additionally, a model to accurately predict monetary costs of creating functional prototypes via AM would be very useful for that same calculus. Monetary costs would be highly dependent on the specific components being developed and the AM technology being used. Experienced Additive Manufacturing engineers could likely make those estimations. However, members within Professor John Hart's Mechanosynthesis Lab at MIT are working on developing a robust cost tool for AM processes that includes both direct manufacturing and operational costs (Shakirov et al., 2020). Being able to quickly get accurate estimations on such costs would further empower a project manager to make quick and sound decisions on the value of ongoing Agile efforts. As mentioned earlier, using a parallel Agile process could also be explored on other aspects of a product beyond later-stage technology integration. Parts that are design dependent on a lot of other components invariably undergo many design changes late in the process. A great example of this in automotive are wiring harnesses. These sometimes simple parts often cost a company a lot of money in retooling. Applying an Agile process with AM prototyping would save on those unnecessary tooling costs. Additionally, corrective changes late in a Phase-Gate process from unforeseen issues are always present. A company would also clearly benefit from building in rapid, Agile iterations at the testing phase that could find corrective solutions quickly and thus not hold up the product's launch.

Finally, as AM becomes more economical for more components, you could start having a substantial part of your product going through the parallel Agile development. One benefit of this could be to allow a company to make many different functional versions of the product. Those distinct versions could then be field tested by actual customers. Here you would be going beyond just figuring out what is technologically feasible. Instead you would be figuring out what is desirable by your customers, and thus maximizing the chances that your product will ultimately be viable and a success in the market before committing substantial resources to its manufacture and launch. This process would require a fundamentally different type of PDP that would need to be created and validated. However, enabling this type of customer feedback would bring complex hardware development closer to the true Agile development that software is able to go through now.

The interest by companies in **Agile Hardware Development** is only growing. **Additive Manufacturing** or 3D printing has also been a hyped technology for multiple decades, but has just recently expanded beyond *design* to *functional* applications. This thesis presents one such way AM technology could help make Agile development a reality for complex and large hardware products. While I cannot be confident that the presented Parallel Agile-Phase-Gate PDP or one like it will become prevalent in industry, I am fairly certain that the Agile methodology and AM technology will be two of the large driving forces that help bring about the inevitable Hardware Revolution.

# Appendix A

# Design Structure Matrix Inputs

## A.1 Normalized Phase-Gate DSM

Figure 6-3 shows the normalized DSM of the Phase-Gate process that was used by Chrysler and introduced by Sequeira (1991).

To simulate the duration of this PDP, the DSM Excel Macro found at www.dsmweb.org Mirshekarian (2015) was used. Details on how to run that macro and how to get the files I used for this thesis can be found in Appendix B. As discussed in Section 5.2, data on rework probability, impact probability, and individual activity durations can be used to create a distribution of simulated process durations.

Figure A-1 shows the rework probability matrix for the normalized Phase-Gate DSM. Figure A-2 shows the impact matrix for the normalized Phase-Gate DSM. And finally, Figure A-3 shows the activity duration data in the form of a best, median, and worst triangular distribution. The learning curve number acts as a multiplier to the rework impacts in order to reduce the impact magnitude due to learning. Example: If LC = 0.2, then 20% of original task duration is required when performing the task in subsequent iterations. And If LC = 1, then 100% of original task duration is required when performing the task in subsequent iterations.

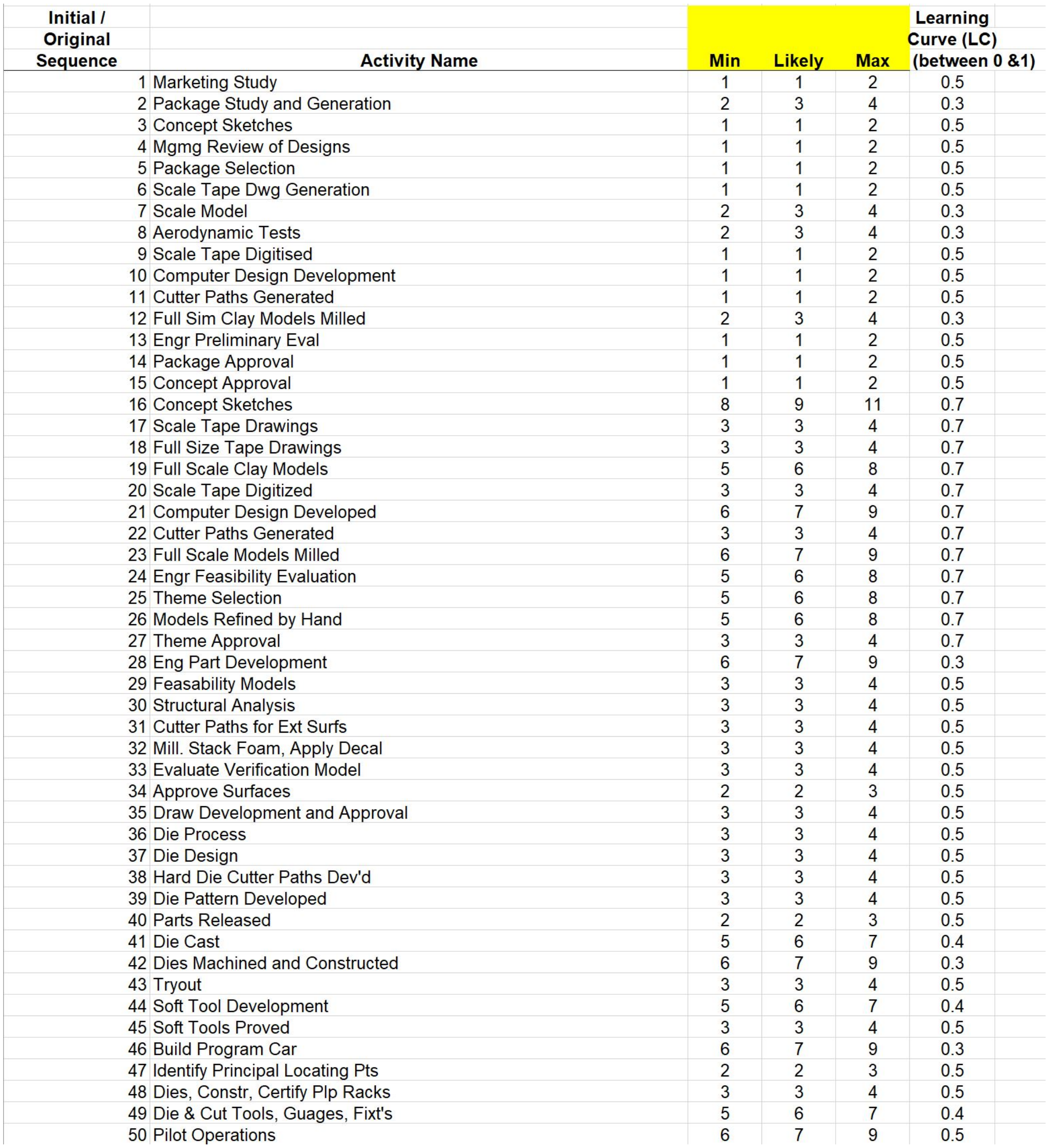
The original DSM from Sequeira did not have this data, instead it just categorized inter-dependencies between activities at one of three levels. But again, the point of this DSM analysis is not to recreate the PDP at Chrysler. It is meant to create a rational baseline to show the feasibility of integrating an Agile process within a given Phase-Gate process. The probability and impact values for this baseline as can be seen in Figures A-1 and A-2 were chosen to be either 0.1 or 0.2. The low range was chosen because a Phase-Gate process is designed to progress steadily and surely forward with limited rework. The activity duration data in Figure A-3 was also not derived from any systematic study. While the relative values have real world basis, the ultimate numbers were chosen to create a PDP that when simulated had a median duration at or very near 100 units and a standard deviation that would equal an uncertainty and possible delays of around one to two months for a 4-5 year long PDP. This was accomplished, as shown in Figure 6-4, with this reference Phase-Gate process having a simulated median duration of 100.5 with a standard deviation of 2.54 over 1000 simulations.

| | |1|2|3|4|5|6|7|8|9|10|11|12|13|14|15|16|17|18|19|20|21|22|23|24|25|26|27|28|29|30|31|32|33|34|35|36|37|38|39|40|41|42|43|44|45|46|47|48|49|50|
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 |||||||||||||||0.2|||||||||||||||||||||||||||||||||||||
| Package Study and Generation | 2 |0.2||||0.2||||||||0.1|0.2|0.2|||||||||||||||||||||||||||||||||||||
| Concept Sketches | 3 |0.1|0.2||0.2|0.1||||||||||0.2|||||||||||||||||||||||||||||||||||||
| Mgmg Review of Designs | 4 |0.1|0.1|0.2||||0.1|||||0.1|||||||||||||||||||||||||||||||||||||||
| Package Selection | 5 ||0.2|0.1|0.2|||0.1|||||0.1|0.2|0.2|0.2|||||||||||||||||||||||||||||||||||||
| Scale Tape Dwg Generation | 6 |||0.2||0.2||||||||||||||||||||||||||||||||||||||||||||||
| Scale Model | 7 |||0.2|0.1|0.1|0.2||0.1|||||||||||||||||||||||||||||||||||||||||||
| Aerodynamic Tests | 8 |||||||0.2|||||0.1|||||||||||||||||||||||||||||||||||||||
| Scale Tape Digitised | 9 ||||||0.2|||||||||||||||||||||||||||||||||||||||||||||
| Computer Design Development | 10 |||0.1||||0.1|0.1|0.2|||0.2||0.1||||||||||||||||||||||||||||||||||||||
| Cutter Paths Generated | 11 ||||||||||0.2|||||||||||||||||||||||||||||||||||||||||
| Full Sim Clay Models Milled | 12 |||||||||||0.2||0.2||0.2|||||||||||||||||||||||||||||||||||||
| Engr Preliminary Eval | 13 |||||||0.1|||0.2||0.1||0.1|0.2|||||||||||||||||||||||||||||||||||||
| Package Approval | 14 ||0.1|||0.2|||||||0.2|0.2||0.2|||||||||||||||||||||||||||||||||||||
| Concept Approval | 15 |0.2|0.1|0.2||0.2|||||||0.2|0.2|0.2||||||||||||||||||||||||||||||||||||||
| Concept Sketches | 16 ||||||||||0.2|||||||0.1|0.1|0.1||0.1||||||0.1|||||||||||||||||||||||||
| Scale Tape Drawings | 17 ||||||||||||||||0.2|||||||||||||||||||||||||||||||||||
| Full Size Tape Drawings | 18 ||||||||||||||||0.2|0.1||0.1||||||||||||||||||||||||||||||||
| Full Scale Clay Models | 19 ||||||||||||||||0.2||0.2|||||||||0.2|0.2|||||||||||||||||||||||||
| Scale Tape Digitized | 20 |||||||||||||||||0.2||||0.1||0.1|||||||||||||||||||||||||||
| Computer Design Developed | 21 ||||||||||||||||0.2|0.1|||0.2||0.1|0.1|0.1||||||||||||||||||||||||||
| Cutter Paths Generated | 22 ||||||||||||||||||||||0.2||0.1|||||||||||||||||||||||||||
| Full Scale Models Milled | 23 ||||||||||||||||0.1||||||0.2||||0.2|0.2|||||||||||||||||||||||||
| Engr Feasibility Evaluation | 24 |||||||||||||||||||0.1||0.2||0.1|||||||||||||||||||||||||||
| Theme Selection | 25 |||||||||||||||||||0.2||||0.2|||0.2|0.2|||||||||||||||||||||||||
| Models Refined by Hand | 26 |||||||||||||||||||||||||0.2||0.2|||||||||||||||||||||||||
| Theme Approval | 27 |||||||||||||||||||||||||0.2|0.2||||||||||||||||||||||||||
| Eng Part Development | 28 |||||||||||||||||||||0.2||||||||0.1|0.1||||0.2|0.2|0.1||||0.2|||||||||||
| Feasability Models | 29 ||||||||||||||||||||||||||||0.2|||||||0.2|||||||||||||||||
| Structural Analysis | 30 ||||||||||||||||||||||||||||0.2|||||||||||0.2|||||||||||
| Cutter Paths for Ext Surfs | 31 ||||||||||||||||||||||||||||0.1||||0.1|0.2|0.2|||||||||||||||||||
| Mill. Stack Foam, Apply Decal | 32 |||||||||||||||||||||||||||||||0.2||0.2|0.2|||||||||||||||||||
| Evaluate Verification Model | 33 ||||||||||||||||||||||||||||||||0.2||0.2|||||||||||||||||||
| Approve Surfaces | 34 ||||||||||||||||||||||||||||0.1||0.1|||0.2||0.1||||||||||||||||||
| Draw Development and Approval | 35 ||||||||||||||||||||||||||||0.2||||||0.2|||||||||||||||||
| Die Process | 36 |||||||||||||||||||||||||||||||||||0.2||0.1|||0.2|||||0.2|0.1|||||
| Die Design | 37 ||||||||||||||||||||||||||||0.2|||||||0.2|0.2|||0.1|0.2|||||||||||
| Hard Die Cutter Paths Dev'd | 38 |||||||||||||||||||||||||||||||||||||0.2||0.2|0.2|||||||||||
| Die Pattern Developed | 39 |||||||||||||||||||||||||||||||||||||0.2|||0.2|||||||||||
| Parts Released | 40 |||||||||||||||||||||||||||||||||||||0.2|0.2|||||||0.2||||||
| Die Cast | 41 |||||||||||||||||||||||||||||||||||||||0.2|0.2||0.1|||||||||
| Dies Machined and Constructed | 42 ||||||||||||||||||||||||||||||||||||||0.2|||0.2||0.2||||||||
| Tryout | 43 ||||||||||||||||||||||||||||||||||||||||||0.2||||||||0.2|
| Soft Tool Development | 44 ||||||||||||||||||||||||||||0.2|||||||||0.2|0.1|||||||0.2||||||
| Soft Tools Proved | 45 |||||||||||||||||||||||||||||||||||||||||||0.2|||||||
| Build Program Car | 46 |||||||||||||||||||||||||||||||||||||0.1|0.1|||||||0.2|||0.2|0.2||
| Identify Principal Locating Pts | 47 ||||||||||||||||||||||||||||0.2||||||||||||||||||||0.1|0.1||
| Dies, Constr, Certify Plp Racks | 48 ||||||||||||||||||||||||||||||||||||||||||||||0.2||||
| Die & Cut Tools, Guages, Fixt's | 49 |||||||||||||||||||||||||||||||||||||||||||||0.1|0.2|0.1||0.2|
| Pilot Operations | 50 ||||||||||||||||||||||||||||||||||||||||||0.2||||0.2|0.2||

Figure A-1: Rework Probability Matrix for the Normalized Phase-Gate DSM

|  |  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 |■|||||||||||||0.2||||||||||||||||||||||||||||||||||||
| Package Study and Generation | 2 |0.2|■|||0.2|||||||0.1|0.2|0.2||||||||||||||||||||||||||||||||||||
| Concept Sketches | 3 |0.1|0.2|■|0.2|0.1||||||||||0.2||||||||||||||||||||||||||||||||||||
| Mgmg Review of Designs | 4 |0.1|0.1|0.2|■|||0.1||||||0.1||||||||||||||||||||||||||||||||||||||
| Package Selection | 5 ||0.2|0.1|0.2|■||0.1|||||0.1|0.2|0.2|0.2||||||||||||||||||||||||||||||||||||
| Scale Tape Dwg Generation | 6 |||0.2||0.2|■|||||||||||||||||||||||||||||||||||||||||||||
| Scale Model | 7 |||0.2|0.1|0.1|0.2|■|0.1|||||||||||||||||||||||||||||||||||||||||||
| Aerodynamic Tests | 8 |||||||0.2|■||||0.1||||||||||||||||||||||||||||||||||||||
| Scale Tape Digitised | 9 ||||||0.2|||■||||||||||||||||||||||||||||||||||||||||||
| Computer Design Development | 10 |||0.1||||0.1|0.1|0.2|■||0.2||0.1||||||||||||||||||||||||||||||||||||||
| Cutter Paths Generated | 11 ||||||||||0.2|■|||||||||||||||||||||||||||||||||||||||
| Full Sim Clay Models Milled | 12 |||||||||||0.2|■|0.2||0.2||||||||||||||||||||||||||||||||||||
| Engr Preliminary Eval | 13 |||||||0.1|||0.2||0.1|■|0.1|0.2||||||||||||||||||||||||||||||||||||
| Package Approval | 14 ||0.1|||0.2|||||||0.2|0.2|■|0.2||||||||||||||||||||||||||||||||||||
| Concept Approval | 15 |0.2|0.1|0.2||0.2|||||||0.2|0.2|0.2|■||||||||||||||||||||||||||||||||||||
| Concept Sketches | 16 ||||||||||0.2||||||■|0.1|0.1|0.1||0.1||||||0.1|||||||||||||||||||||||
| Scale Tape Drawings | 17 |||||||||||||||||0.2|■|||||||||||||||||||||||||||||||||||
| Full Size Tape Drawings | 18 |||||||||||||||||0.2|0.1|■|0.1||||||||||||||||||||||||||||||||
| Full Scale Clay Models | 19 |||||||||||||||||0.2||0.2|■|||||||0.2|0.2|||||||||||||||||||||||
| Scale Tape Digitized | 20 ||||||||||||||||||0.2|||■|0.1||0.1||||||||||||||||||||||||||||
| Computer Design Developed | 21 |||||||||||||||||0.2|0.1|||0.2|■|0.1|0.1|0.1||||||||||||||||||||||||||
| Cutter Paths Generated | 22 |||||||||||||||||||||0.2|■|0.1||||||||||||||||||||||||||||
| Full Scale Models Milled | 23 |||||||||||||||||0.1||||||0.2|■|||0.2|0.2|||||||||||||||||||||||
| Engr Feasibility Evaluation | 24 ||||||||||||||||||||0.1||0.2||0.1|■||||||||||||||||||||||||||
| Theme Selection | 25 ||||||||||||||||||||0.2||||0.2||■|0.2|0.2|||||||||||||||||||||||
| Models Refined by Hand | 26 |||||||||||||||||||||||||0.2|■|0.2|||||||||||||||||||||||
| Theme Approval | 27 |||||||||||||||||||||||||0.2|0.2|■|||||||||||||||||||||||
| Eng Part Development | 28 |||||||||||||||||||||0.2|||||||■|0.1|0.1||||0.2|0.2|0.1||||0.2|||||||||||
| Feasability Models | 29 ||||||||||||||||||||||||||||0.2|■|||||0.2|||||||||||||||||
| Structural Analysis | 30 ||||||||||||||||||||||||||||0.2||■||||||||||0.2|||||||||||
| Cutter Paths for Ext Surfs | 31 ||||||||||||||||||||||||||||0.1|||■|0.1|0.2|0.2|||||||||||||||||
| Mill. Stack Foam, Apply Decal | 32 |||||||||||||||||||||||||||||||0.2|■|0.2|0.2|||||||||||||||||
| Evaluate Verification Model | 33 ||||||||||||||||||||||||||||||||0.2|■|0.2|||||||||||||||||
| Approve Surfaces | 34 ||||||||||||||||||||||||||||0.1||0.1|||0.2|■|0.1|||||||||||||||
| Draw Development and Approval | 35 ||||||||||||||||||||||||||||0.2||||||0.2|■|||||||||||||||
| Die Process | 36 |||||||||||||||||||||||||||||||||||0.2|■|0.1|||0.2|||||0.2|0.1|||||
| Die Design | 37 ||||||||||||||||||||||||||||0.2||||||||0.2|0.2|■||0.1|0.2|||||||||||
| Hard Die Cutter Paths Dev'd | 38 |||||||||||||||||||||||||||||||||||||0.2|■|0.2|0.2|||||||||||
| Die Pattern Developed | 39 |||||||||||||||||||||||||||||||||||||0.2||■|0.2|||||||||||
| Parts Released | 40 |||||||||||||||||||||||||||||||||||||0.2|0.2||■|||||0.2|||||
| Die Cast | 41 |||||||||||||||||||||||||||||||||||||||0.2|0.2|■|0.1||||||||
| Dies Machined and Constructed | 42 ||||||||||||||||||||||||||||||||||||||0.2|||0.2|■|0.2|||||||
| Tryout | 43 ||||||||||||||||||||||||||||||||||||||||||0.2|■|||||||0.2|
| Soft Tool Development | 44 ||||||||||||||||||||||||||||0.2||||||||||0.2|0.1||||||■|0.2|||||
| Soft Tools Proved | 45 |||||||||||||||||||||||||||||||||||||||||||0.2|■|||||
| Build Program Car | 46 |||||||||||||||||||||||||||||||||||||0.1|0.1||||||||0.2|■||0.2|0.2||
| Identify Principal Locating Pts | 47 ||||||||||||||||||||||||||||0.2|||||||||||||||||||■|0.1|0.1||
| Dies, Constr, Certify Plp Racks | 48 ||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||
| Die & Cut Tools, Guages, Fixt's | 49 |||||||||||||||||||||||||||||||||||||||||||||0.1|0.2|0.1|■|0.2|
| Pilot Operations | 50 ||||||||||||||||||||||||||||||||||||||||||0.2||||0.2|0.2|■|

Figure A-2: Impact Matrix for the Normalized Phase-Gate DSM



| Initial / | | | | | Learning |
|---|---|---|---|---|---|
| Original | | | | | Curve (LC) |
| Sequence | Activity Name | Min | Likely | Max | (between 0 &1) |
| 1 | Marketing Study | 1 | 1 | 2 | 0.5 |
| 2 | Package Study and Generation | 2 | 3 | 4 | 0.3 |
| 3 | Concept Sketches | 1 | 1 | 2 | 0.5 |
| 4 | Mgmg Review of Designs | 1 | 1 | 2 | 0.5 |
| 5 | Package Selection | 1 | 1 | 2 | 0.5 |
| 6 | Scale Tape Dwg Generation | 1 | 1 | 2 | 0.5 |
| 7 | Scale Model | 2 | 3 | 4 | 0.3 |
| 8 | Aerodynamic Tests | 2 | 3 | 4 | 0.3 |
| 9 | Scale Tape Digitised | 1 | 1 | 2 | 0.5 |
| 10 | Computer Design Development | 1 | 1 | 2 | 0.5 |
| 11 | Cutter Paths Generated | 1 | 1 | 2 | 0.5 |
| 12 | Full Sim Clay Models Milled | 2 | 3 | 4 | 0.3 |
| 13 | Engr Preliminary Eval | 1 | 1 | 2 | 0.5 |
| 14 | Package Approval | 1 | 1 | 2 | 0.5 |
| 15 | Concept Approval | 1 | 1 | 2 | 0.5 |
| 16 | Concept Sketches | 8 | 9 | 11 | 0.7 |
| 17 | Scale Tape Drawings | 3 | 3 | 4 | 0.7 |
| 18 | Full Size Tape Drawings | 3 | 3 | 4 | 0.7 |
| 19 | Full Scale Clay Models | 5 | 6 | 8 | 0.7 |
| 20 | Scale Tape Digitized | 3 | 3 | 4 | 0.7 |
| 21 | Computer Design Developed | 6 | 7 | 9 | 0.7 |
| 22 | Cutter Paths Generated | 3 | 3 | 4 | 0.7 |
| 23 | Full Scale Models Milled | 6 | 7 | 9 | 0.7 |
| 24 | Engr Feasibility Evaluation | 5 | 6 | 8 | 0.7 |
| 25 | Theme Selection | 5 | 6 | 8 | 0.7 |
| 26 | Models Refined by Hand | 5 | 6 | 8 | 0.7 |
| 27 | Theme Approval | 3 | 3 | 4 | 0.7 |
| 28 | Eng Part Development | 6 | 7 | 9 | 0.3 |
| 29 | Feasability Models | 3 | 3 | 4 | 0.5 |
| 30 | Structural Analysis | 3 | 3 | 4 | 0.5 |
| 31 | Cutter Paths for Ext Surfs | 3 | 3 | 4 | 0.5 |
| 32 | Mill. Stack Foam, Apply Decal | 3 | 3 | 4 | 0.5 |
| 33 | Evaluate Verification Model | 3 | 3 | 4 | 0.5 |
| 34 | Approve Surfaces | 2 | 2 | 3 | 0.5 |
| 35 | Draw Development and Approval | 3 | 3 | 4 | 0.5 |
| 36 | Die Process | 3 | 3 | 4 | 0.5 |
| 37 | Die Design | 3 | 3 | 4 | 0.5 |
| 38 | Hard Die Cutter Paths Dev'd | 3 | 3 | 4 | 0.5 |
| 39 | Die Pattern Developed | 3 | 3 | 4 | 0.5 |
| 40 | Parts Released | 2 | 2 | 3 | 0.5 |
| 41 | Die Cast | 5 | 6 | 7 | 0.4 |
| 42 | Dies Machined and Constructed | 6 | 7 | 9 | 0.3 |
| 43 | Tryout | 3 | 3 | 4 | 0.5 |
| 44 | Soft Tool Development | 5 | 6 | 7 | 0.4 |
| 45 | Soft Tools Proved | 3 | 3 | 4 | 0.5 |
| 46 | Build Program Car | 6 | 7 | 9 | 0.3 |
| 47 | Identify Principal Locating Pts | 2 | 2 | 3 | 0.5 |
| 48 | Dies, Constr, Certify Plp Racks | 3 | 3 | 4 | 0.5 |
| 49 | Die & Cut Tools, Guages, Fixt's | 5 | 6 | 7 | 0.4 |
| 50 | Pilot Operations | 6 | 7 | 9 | 0.5 |

Figure A-3: Activity Duration Data for the Normalized Phase-Gate DSM

## A.2 Coates Parallel Agile-Phase-Gate DSM

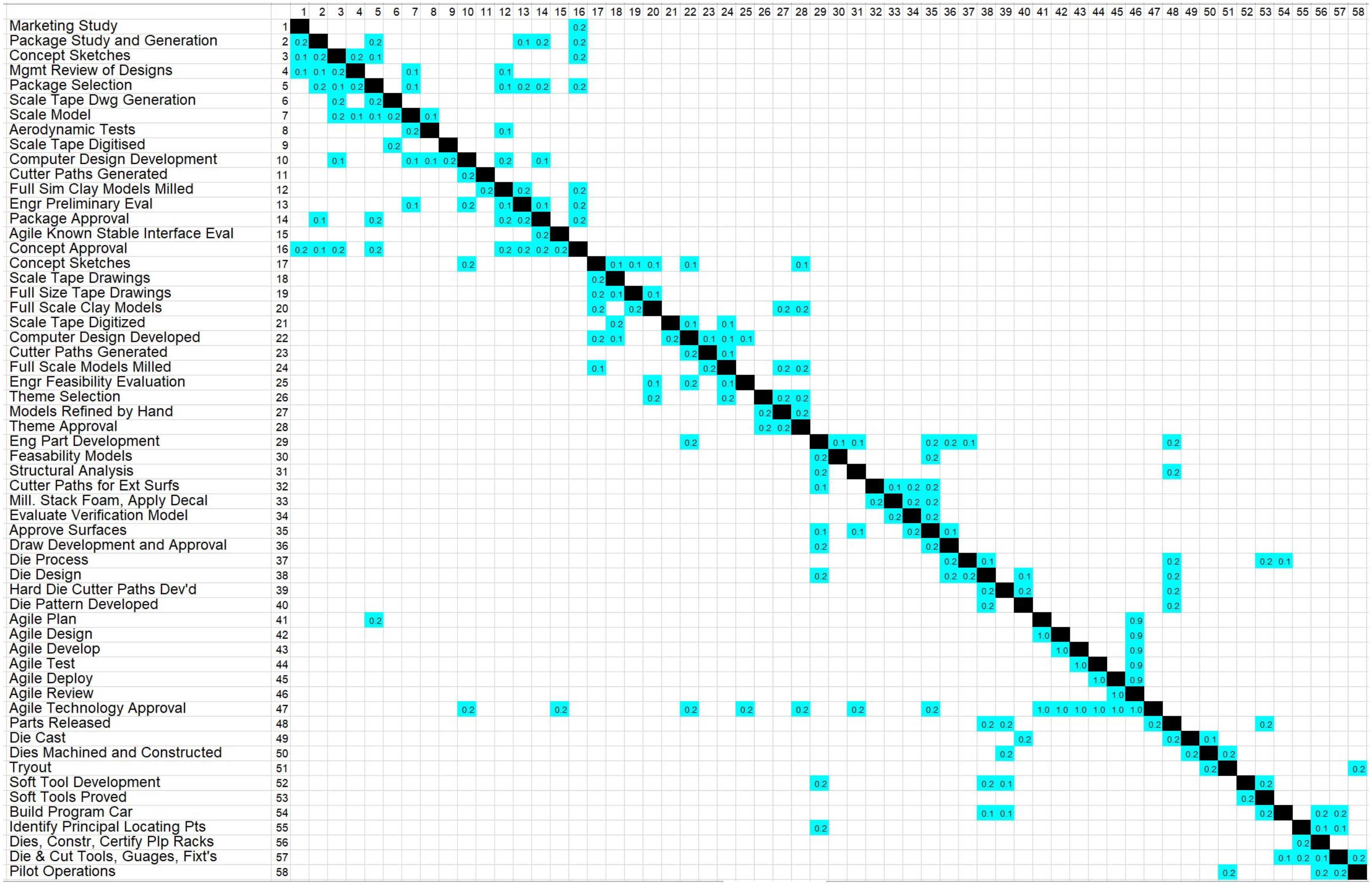
Figure A-4 shows the rework probability matrix for the Parallel Agile-Phase-Gate process as shown in Figure 7-5. Figure A-5 shows the impact matrix for this process. And finally, Figure A-6 shows the activity duration data.

This data is almost identical to the matrices and duration distributions as presented in the previous Appendix Section A.1, except for the inclusion of the representative Agile process that was discussed in Section 7.1. You can see that Agile process was inserted as steps 41-47 in the matrices. The parallel Agile process is kicked off by step 5, Package Selection. The process has a high chance of iterating (90% each time) as shown in the probability entries above the diagonal of 0.9. Note: it would have been more straightforward for simulation purposes to just create two steps, *Start Agile Sprint* and *Review Agile Sprint* with a 90% probability of having to go back to 'Start' after 'Review,' but I put in the intermediate steps just to make the Agile process more explicit and noticeable in the DSM. The impact of rework within the Agile process is 1.0 with a 1.0 learning curve, meaning that when a step has to be redone, it has to be redone in its entirety. As mentioned in Section 7.1, this simulates the time boxed sprints of an Agile process.

It could be argued that it might be more accurate to model an Agile process as having near 100% chance of rework for the first few sprints as the base work is accomplished. This could have been followed by decreasing chances of iteration as the process converged around a yet-to-be-known solution. However, simulating a DSM with progressively decreasing rework probability was not possible in the Macro. I could have created a series of process steps, each representing a subsequent Agile iteration with a decreasing probability of rework value. However, the ultimate result would not have been different in any meaningful way from the the distribution of Agile process durations as shown in Figure 7-3. Both ways of simulating the Agile process end up with a duration distribution that has a high standard deviation in relation to its median value, with a right tail of instances that fail to complete in a timely manner. And thus the overall PDP durations the model ultimately output in

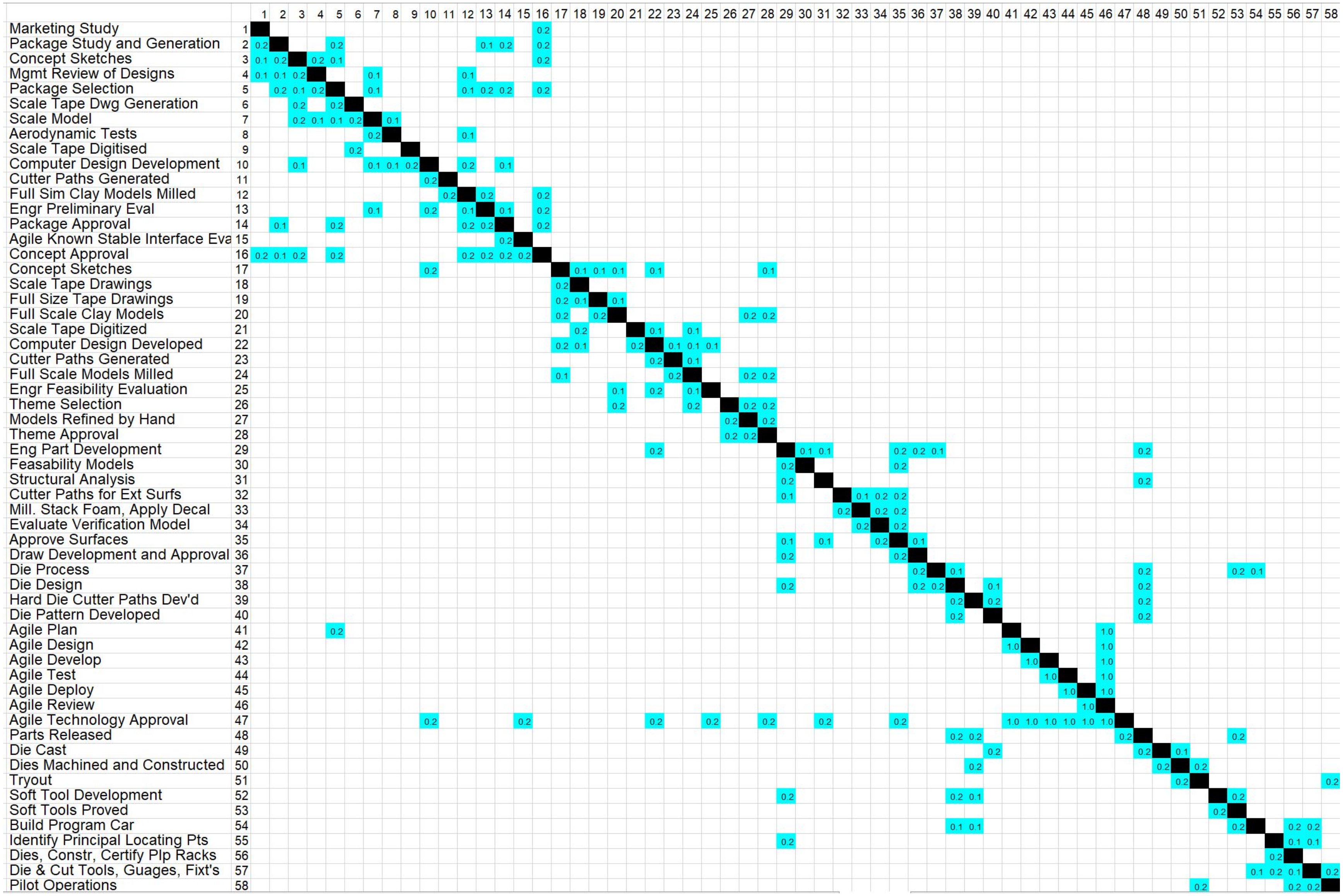
Figure 7-6 would not have been significantly different.

In the end, each sprint having a uniform high chance of requiring to be redone was chosen for the sake of the DSM's interpretability and simplicity of analysis.



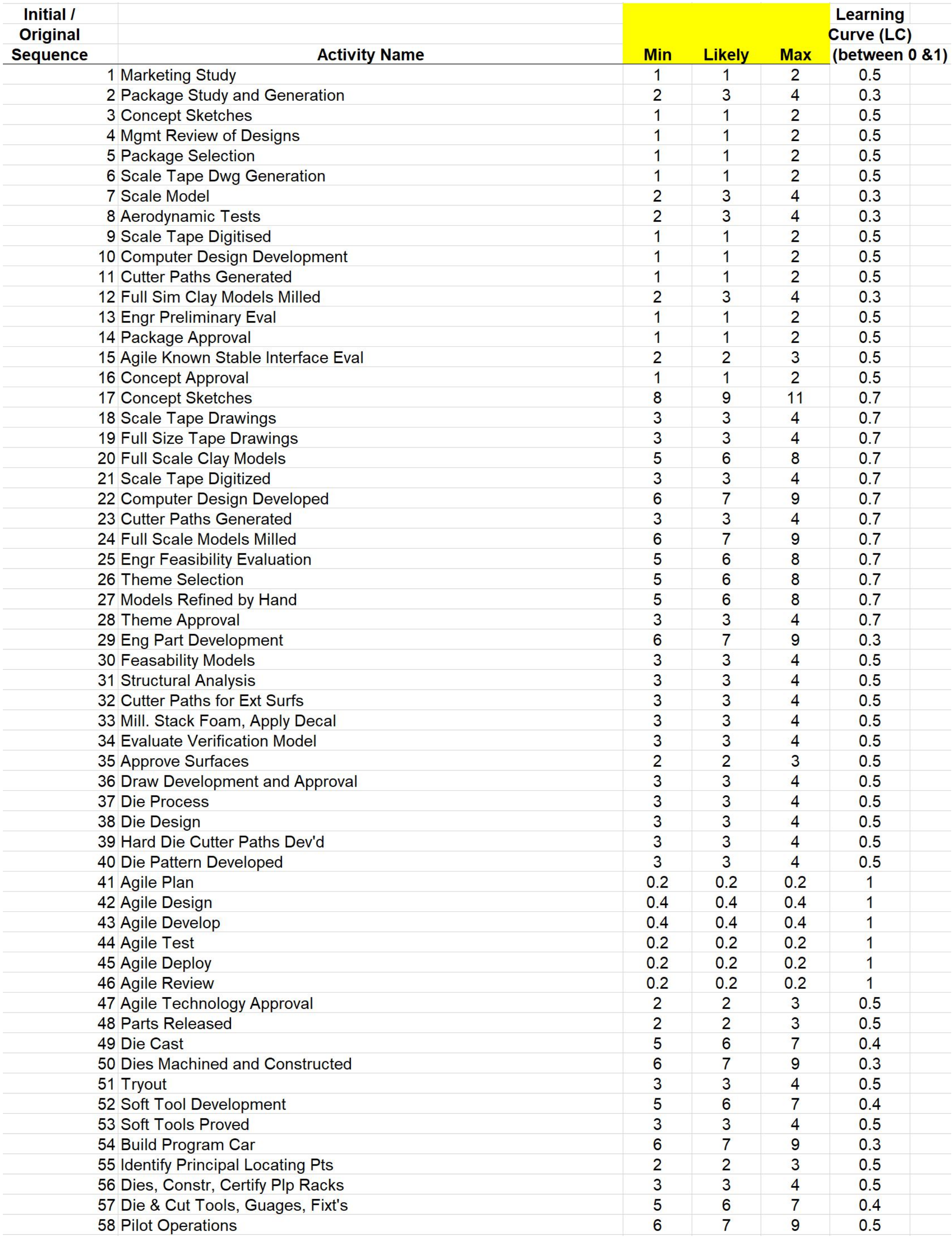
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 | ■ | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Study and Generation | 2 | 0.2 | ■ | | | 0.2 | | | | | | | | 0.1 | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 3 | 0.1 | 0.2 | ■ | 0.2 | 0.1 | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mgmt Review of Designs | 4 | 0.1 | 0.1 | 0.2 | ■ | | | 0.1 | | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Selection | 5 | | 0.2 | 0.1 | 0.2 | ■ | | 0.1 | | | | | 0.1 | 0.2 | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Dwg Generation | 6 | | | 0.2 | | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Model | 7 | | | 0.2 | 0.1 | 0.1 | 0.2 | ■ | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aerodynamic Tests | 8 | | | | | | | 0.2 | ■ | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitised | 9 | | | | | | 0.2 | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Development | 10 | | | 0.1 | | | | 0.1 | 0.1 | 0.2 | ■ | | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 11 | | | | | | | | | | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Sim Clay Models Milled | 12 | | | | | | | | | | | 0.2 | ■ | 0.2 | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Preliminary Eval | 13 | | | | | | | 0.1 | | | 0.2 | | 0.1 | ■ | 0.1 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Approval | 14 | | 0.1 | | | 0.2 | | | | | | | 0.2 | 0.2 | ■ | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agile Known Stable Interface Eval | 15 | | | | | | | | | | | | | | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Approval | 16 | 0.2 | 0.1 | 0.2 | | 0.2 | | | | | | | 0.2 | 0.2 | 0.2 | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 17 | | | | | | | | | | 0.2 | | | | | | | ■ | 0.1 | 0.1 | 0.1 | | 0.1 | | | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Drawings | 18 | | | | | | | | | | | | | | | | | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Size Tape Drawings | 19 | | | | | | | | | | | | | | | | | 0.2 | 0.1 | ■ | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Clay Models | 20 | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | ■ | | | | | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitized | 21 | | | | | | | | | | | | | | | | | | 0.2 | | | ■ | 0.1 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Developed | 22 | | | | | | | | | | | | | | | | | 0.2 | 0.1 | | | 0.2 | ■ | 0.1 | 0.1 | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 23 | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Models Milled | 24 | | | | | | | | | | | | | | | | | 0.1 | | | | | | 0.2 | ■ | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Feasibility Evaluation | 25 | | | | | | | | | | | | | | | | | | | | 0.1 | | 0.2 | | 0.1 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Selection | 26 | | | | | | | | | | | | | | | | | | | | 0.2 | | | | 0.2 | | ■ | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Models Refined by Hand | 27 | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Approval | 28 | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eng Part Development | 29 | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | ■ | 0.1 | 0.1 | | | | 0.2 | 0.2 | 0.1 | | | | | | | | | | | 0.2 | | | | | | | | | | |
| Feasability Models | 30 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Structural Analysis | 31 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | ■ | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | |
| Cutter Paths for Ext Surfs | 32 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | | | ■ | 0.1 | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Mill. Stack Foam, Apply Decal | 33 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Evaluate Verification Model | 34 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Approve Surfaces | 35 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | | 0.1 | | | 0.2 | ■ | 0.1 | | | | | | | | | | | | | | | | | | | | | | |
| Draw Development and Approval | 36 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | 0.2 | ■ | | | | | | | | | | | | | | | | | | | | | | |
| Die Process | 37 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.1 | | | | | | | | | | 0.2 | | | | | 0.2 | 0.1 | | | | |
| Die Design | 38 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | 0.2 | 0.2 | ■ | | 0.1 | | | | | | | | 0.2 | | | | | | | | | | |
| Hard Die Cutter Paths Dev'd | 39 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | 0.2 | | | | | | | | 0.2 | | | | | | | | | | |
| Die Pattern Developed | 40 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | ■ | | | | | | | | 0.2 | | | | | | | | | | |
| Agile Plan | 41 | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | 0.9 | | | | | | | | | | | | |
| Agile Design | 42 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | ■ | | | | 0.9 | | | | | | | | | | | | |
| Agile Develop | 43 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | ■ | | | 0.9 | | | | | | | | | | | | |
| Agile Test | 44 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | ■ | | 0.9 | | | | | | | | | | | | |
| Agile Deploy | 45 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | ■ | 0.9 | | | | | | | | | | | | |
| Agile Review | 46 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | ■ | | | | | | | | | | | | |
| Agile Technology Approval | 47 | | | | | | | | | | 0.2 | | | | | 0.2 | | | | | | | 0.2 | | | 0.2 | | | 0.2 | | | 0.2 | | | | 0.2 | | | | | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | ■ | | | | | | | | | | | |
| Parts Released | 48 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | 0.2 | | | | | | | | 0.2 | ■ | | | | | 0.2 | | | | | |
| Die Cast | 49 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | 0.2 | ■ | 0.1 | | | | | | | | |
| Dies Machined and Constructed | 50 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | 0.2 | ■ | 0.2 | | | | | | | |
| Tryout | 51 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | | | | | | | 0.2 |
| Soft Tool Development | 52 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | 0.2 | 0.1 | | | | | | | | | | | | | ■ | 0.2 | | | | | |
| Soft Tools Proved | 53 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | | | | | |
| Build Program Car | 54 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | 0.1 | | | | | | | | | | | | | | 0.2 | ■ | | 0.2 | 0.2 | |
| Identify Principal Locating Pts | 55 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | 0.1 | 0.1 | |
| Dies, Constr, Certify Plp Racks | 56 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | ■ | | |
| Die & Cut Tools, Guages, Fixt's | 57 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | 0.2 | 0.1 | ■ | 0.2 |
| Pilot Operations | 58 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | 0.2 | 0.2 | ■ |

Figure A-4: Rework Probability Matrix for the Parallel Agile-Phase-Gate DSM



| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marketing Study | 1 | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Study and Generation | 2 | 0.2 | | | | 0.2 | | | | | | | | 0.1 | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 3 | 0.1 | 0.2 | | 0.2 | 0.1 | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Mgmt Review of Designs | 4 | 0.1 | 0.1 | 0.2 | | | | 0.1 | | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Selection | 5 | | 0.2 | 0.1 | 0.2 | | | 0.1 | | | | | 0.1 | 0.2 | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Dwg Generation | 6 | | | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Model | 7 | | | 0.2 | 0.1 | 0.1 | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aerodynamic Tests | 8 | | | | | | | 0.2 | | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitised | 9 | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Development | 10 | | | 0.1 | | | | 0.1 | 0.1 | 0.2 | | | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 11 | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Sim Clay Models Milled | 12 | | | | | | | | | | | 0.2 | | 0.2 | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Preliminary Eval | 13 | | | | | | | 0.1 | | | 0.2 | | 0.1 | | 0.1 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Package Approval | 14 | | 0.1 | | | 0.2 | | | | | | | 0.2 | 0.2 | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agile Known Stable Interface Eva | 15 | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Approval | 16 | 0.2 | 0.1 | 0.2 | | 0.2 | | | | | | | 0.2 | 0.2 | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concept Sketches | 17 | | | | | | | | | | 0.2 | | | | | | | | 0.1 | 0.1 | 0.1 | | 0.1 | | | | | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Drawings | 18 | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Size Tape Drawings | 19 | | | | | | | | | | | | | | | | | 0.2 | 0.1 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Clay Models | 20 | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | | | | | | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Scale Tape Digitized | 21 | | | | | | | | | | | | | | | | | | 0.2 | | | | 0.1 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Computer Design Developed | 22 | | | | | | | | | | | | | | | | | 0.2 | 0.1 | | | 0.2 | | 0.1 | 0.1 | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cutter Paths Generated | 23 | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Full Scale Models Milled | 24 | | | | | | | | | | | | | | | | | 0.1 | | | | | | 0.2 | | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engr Feasibility Evaluation | 25 | | | | | | | | | | | | | | | | | | | | 0.1 | | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Selection | 26 | | | | | | | | | | | | | | | | | | | | 0.2 | | | | 0.2 | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Models Refined by Hand | 27 | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Theme Approval | 28 | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eng Part Development | 29 | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | 0.1 | 0.1 | | | | 0.2 | 0.2 | 0.1 | | | | | | | | | | | 0.2 | | | | | | | | | | |
| Feasability Models | 30 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Structural Analysis | 31 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | |
| Cutter Paths for Ext Surfs | 32 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | | | | 0.1 | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Mill. Stack Foam, Apply Decal | 33 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Evaluate Verification Model | 34 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Approve Surfaces | 35 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | | 0.1 | | | 0.2 | | 0.1 | | | | | | | | | | | | | | | | | | | | | | |
| Draw Development and Approval | 36 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | |
| Die Process | 37 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.1 | | | | | | | | | | 0.2 | | | | | 0.2 | 0.1 | | | | |
| Die Design | 38 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | 0.2 | 0.2 | | | 0.1 | | | | | | | | 0.2 | | | | | | | | | | |
| Hard Die Cutter Paths Dev'd | 39 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | 0.2 | | | | | | | | 0.2 | | | | | | | | | | |
| Die Pattern Developed | 40 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | 0.2 | | | | | | | | | | |
| Agile Plan | 41 | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | | | | | | | | | | | |
| Agile Design | 42 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | | | | 1.0 | | | | | | | | | | | | |
| Agile Develop | 43 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | | | 1.0 | | | | | | | | | | | | |
| Agile Test | 44 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | | 1.0 | | | | | | | | | | | | |
| Agile Deploy | 45 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | 1.0 | | | | | | | | | | | | |
| Agile Review | 46 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1.0 | | | | | | | | | | | | | |
| Agile Technology Approval | 47 | | | | | | | | | | 0.2 | | | | | 0.2 | | | | | | | 0.2 | | | 0.2 | | | 0.2 | | | 0.2 | | | | 0.2 | | | | | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | | | | | | | | | | | |
| Parts Released | 48 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | 0.2 | | | | | | | | 0.2 | | | | | | 0.2 | | | | | |
| Die Cast | 49 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | 0.2 | | 0.1 | | | | | | | | |
| Dies Machined and Constructed | 50 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | 0.2 | | 0.2 | | | | | | | |
| Tryout | 51 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | 0.2 |
| Soft Tool Development | 52 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | 0.2 | 0.1 | | | | | | | | | | | | | | 0.2 | | | | | |
| Soft Tools Proved | 53 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | |
| Build Program Car | 54 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | 0.1 | | | | | | | | | | | | | | 0.2 | | | 0.2 | 0.2 | |
| Identify Principal Locating Pts | 55 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | 0.1 | |
| Dies, Constr, Certify Plp Racks | 56 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | |
| Die & Cut Tools, Guages, Fixt's | 57 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.1 | 0.2 | 0.1 | | 0.2 |
| Pilot Operations | 58 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.2 | | | | | 0.2 | 0.2 | |

Figure A-5: Impact Matrix for the Parallel Agile-Phase-Gate DSM



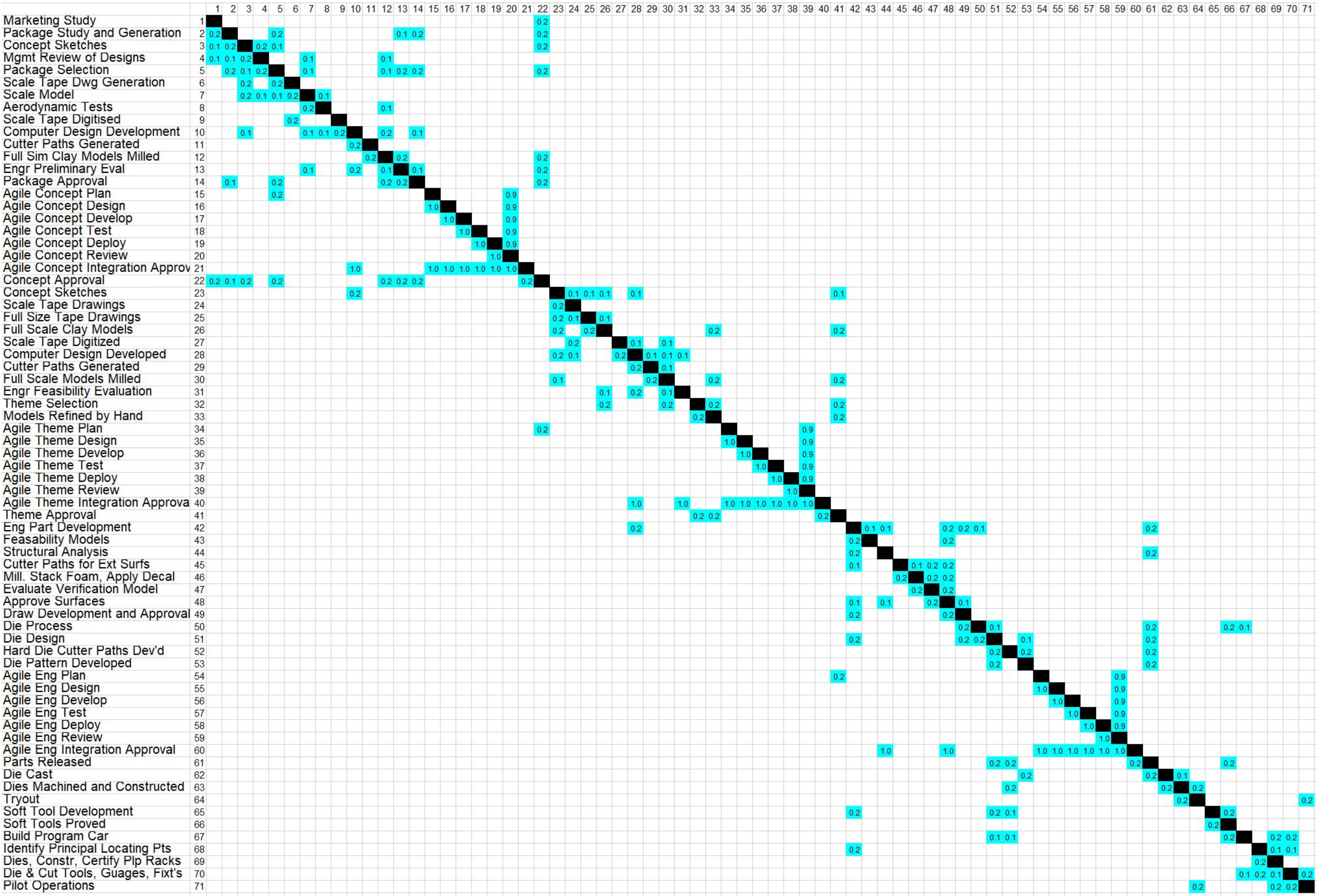
| Initial / | | | | | Learning |
|---|---|---|---|---|---|
| Original | | | | | Curve (LC) |
| Sequence | Activity Name | Min | Likely | Max | (between 0 &1) |
| 1 | Marketing Study | 1 | 1 | 2 | 0.5 |
| 2 | Package Study and Generation | 2 | 3 | 4 | 0.3 |
| 3 | Concept Sketches | 1 | 1 | 2 | 0.5 |
| 4 | Mgmt Review of Designs | 1 | 1 | 2 | 0.5 |
| 5 | Package Selection | 1 | 1 | 2 | 0.5 |
| 6 | Scale Tape Dwg Generation | 1 | 1 | 2 | 0.5 |
| 7 | Scale Model | 2 | 3 | 4 | 0.3 |
| 8 | Aerodynamic Tests | 2 | 3 | 4 | 0.3 |
| 9 | Scale Tape Digitised | 1 | 1 | 2 | 0.5 |
| 10 | Computer Design Development | 1 | 1 | 2 | 0.5 |
| 11 | Cutter Paths Generated | 1 | 1 | 2 | 0.5 |
| 12 | Full Sim Clay Models Milled | 2 | 3 | 4 | 0.3 |
| 13 | Engr Preliminary Eval | 1 | 1 | 2 | 0.5 |
| 14 | Package Approval | 1 | 1 | 2 | 0.5 |
| 15 | Agile Known Stable Interface Eval | 2 | 2 | 3 | 0.5 |
| 16 | Concept Approval | 1 | 1 | 2 | 0.5 |
| 17 | Concept Sketches | 8 | 9 | 11 | 0.7 |
| 18 | Scale Tape Drawings | 3 | 3 | 4 | 0.7 |
| 19 | Full Size Tape Drawings | 3 | 3 | 4 | 0.7 |
| 20 | Full Scale Clay Models | 5 | 6 | 8 | 0.7 |
| 21 | Scale Tape Digitized | 3 | 3 | 4 | 0.7 |
| 22 | Computer Design Developed | 6 | 7 | 9 | 0.7 |
| 23 | Cutter Paths Generated | 3 | 3 | 4 | 0.7 |
| 24 | Full Scale Models Milled | 6 | 7 | 9 | 0.7 |
| 25 | Engr Feasibility Evaluation | 5 | 6 | 8 | 0.7 |
| 26 | Theme Selection | 5 | 6 | 8 | 0.7 |
| 27 | Models Refined by Hand | 5 | 6 | 8 | 0.7 |
| 28 | Theme Approval | 3 | 3 | 4 | 0.7 |
| 29 | Eng Part Development | 6 | 7 | 9 | 0.3 |
| 30 | Feasability Models | 3 | 3 | 4 | 0.5 |
| 31 | Structural Analysis | 3 | 3 | 4 | 0.5 |
| 32 | Cutter Paths for Ext Surfs | 3 | 3 | 4 | 0.5 |
| 33 | Mill. Stack Foam, Apply Decal | 3 | 3 | 4 | 0.5 |
| 34 | Evaluate Verification Model | 3 | 3 | 4 | 0.5 |
| 35 | Approve Surfaces | 2 | 2 | 3 | 0.5 |
| 36 | Draw Development and Approval | 3 | 3 | 4 | 0.5 |
| 37 | Die Process | 3 | 3 | 4 | 0.5 |
| 38 | Die Design | 3 | 3 | 4 | 0.5 |
| 39 | Hard Die Cutter Paths Dev'd | 3 | 3 | 4 | 0.5 |
| 40 | Die Pattern Developed | 3 | 3 | 4 | 0.5 |
| 41 | Agile Plan | 0.2 | 0.2 | 0.2 | 1 |
| 42 | Agile Design | 0.4 | 0.4 | 0.4 | 1 |
| 43 | Agile Develop | 0.4 | 0.4 | 0.4 | 1 |
| 44 | Agile Test | 0.2 | 0.2 | 0.2 | 1 |
| 45 | Agile Deploy | 0.2 | 0.2 | 0.2 | 1 |
| 46 | Agile Review | 0.2 | 0.2 | 0.2 | 1 |
| 47 | Agile Technology Approval | 2 | 2 | 3 | 0.5 |
| 48 | Parts Released | 2 | 2 | 3 | 0.5 |
| 49 | Die Cast | 5 | 6 | 7 | 0.4 |
| 50 | Dies Machined and Constructed | 6 | 7 | 9 | 0.3 |
| 51 | Tryout | 3 | 3 | 4 | 0.5 |
| 52 | Soft Tool Development | 5 | 6 | 7 | 0.4 |
| 53 | Soft Tools Proved | 3 | 3 | 4 | 0.5 |
| 54 | Build Program Car | 6 | 7 | 9 | 0.3 |
| 55 | Identify Principal Locating Pts | 2 | 2 | 3 | 0.5 |
| 56 | Dies, Constr, Certify Plp Racks | 3 | 3 | 4 | 0.5 |
| 57 | Die & Cut Tools, Guages, Fixt's | 5 | 6 | 7 | 0.4 |
| 58 | Pilot Operations | 6 | 7 | 9 | 0.5 |

Figure A-6: Activity Duration Data for the Parallel Agile-Phase-Gate DSM

## A.3 Cooper Hybrid Agile-Phase-Gate DSM

Figure A-7 shows the rework probability matrix for the Parallel Agile-Phase-Gate process as shown in Figure 7-8. Figure A-8 shows the impact matrix for this process. And finally, Figure A-9 shows the activity duration data.

The inputs to these matrices are similar to the one in the previous section, except now there are three Agile processes that need to be completed by the end of each of those phases and approved at the required gate. As mentioned in Section 7.5, this simulation is not meant to imply that a process that follows this type of integration of Agile development within individual phases would in fact see durations that are on average 37.5% longer and would have untenable standard deviations as shown in Figure 7-9. What this simulation is attempting to show is that if you were to construct a PDP like this, you would have to somehow limit the amount of iterations or limit the scope of what that Agile process is trying to solve in order to not have vast overruns. This would in turn limit the effectiveness of that Agile development.

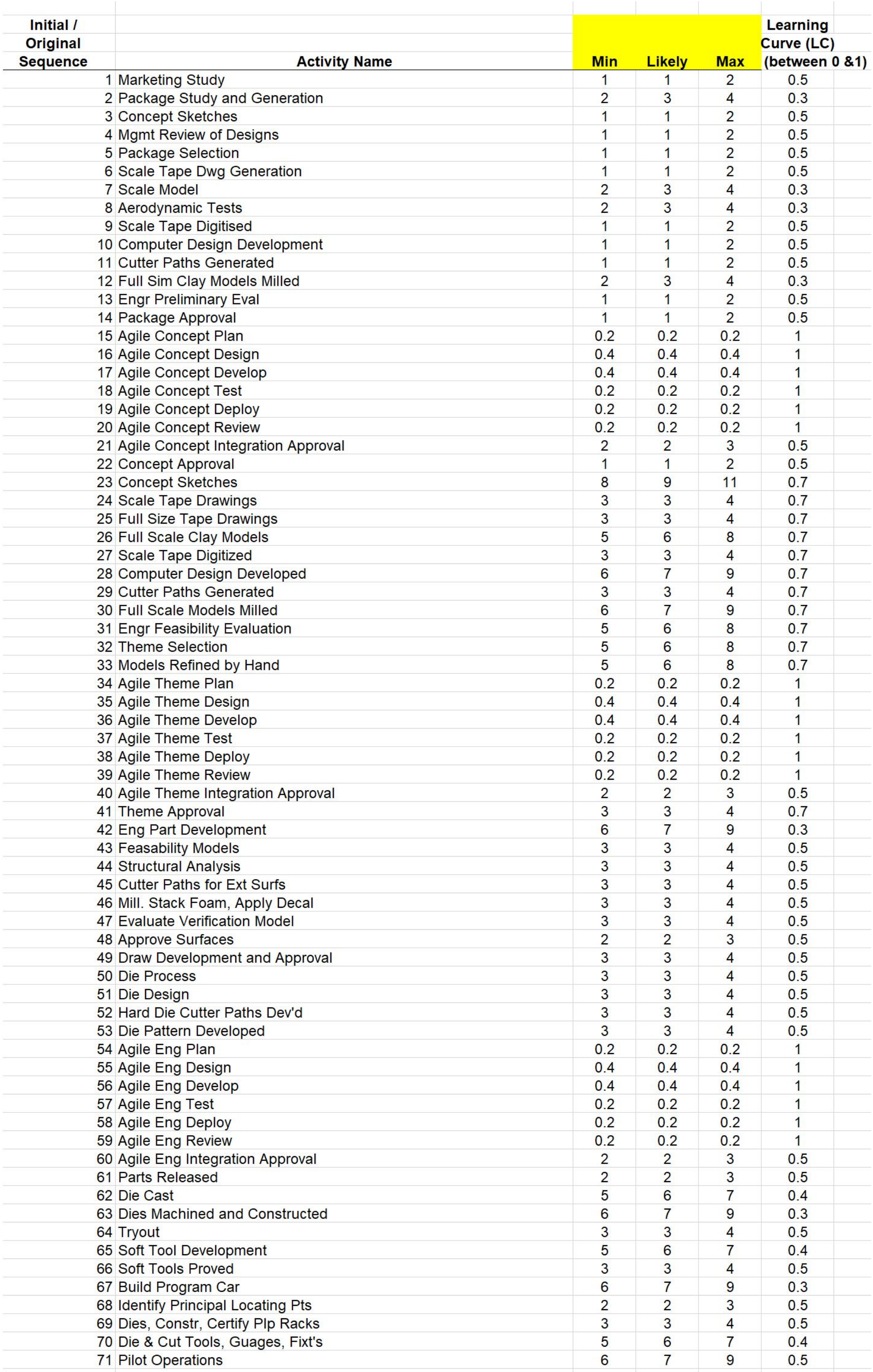


| | |1|2|3|4|5|6|7|8|9|10|11|12|13|14|15|16|17|18|19|20|21|22|23|24|25|26|27|28|29|30|31|32|33|34|35|36|37|38|39|40|41|42|43|44|45|46|47|48|49|50|51|52|53|54|55|56|57|58|59|60|61|62|63|64|65|66|67|68|69|70|71|
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|Marketing Study|1|■|||||||||||||||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Study and Generation|2|0.2|■|||0.2||||||||0.1|0.2||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Sketches|3|0.1|0.2|■|0.2|0.1|||||||||||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Mgmt Review of Designs|4|0.1|0.1|0.2|■|||0.1|||||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Selection|5||0.2|0.1|0.2|■||0.1|||||0.1|0.2|0.2||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Tape Dwg Generation|6|||0.2||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Model|7|||0.2|0.1|0.1|0.2|■|0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Aerodynamic Tests|8|||||||0.2|■||||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Tape Digitised|9||||||0.2|||■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Computer Design Development|10|||0.1||||0.1|0.1|0.2|■||0.2||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Cutter Paths Generated|11||||||||||0.2|■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Full Sim Clay Models Milled|12|||||||||||0.2|■|0.2|||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Engr Preliminary Eval|13|||||||0.1|||0.2||0.1|■|0.1||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Approval|14||0.1|||0.2|||||||0.2|0.2|■||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Plan|15|||||0.2||||||||||■|||||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Design|16|||||||||||||||1.0|■||||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Develop|17||||||||||||||||1.0|■|||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Test|18|||||||||||||||||1.0|■||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Deploy|19||||||||||||||||||1.0|■|0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Review|20|||||||||||||||||||1.0|■||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Integration Approv|21||||||||||1.0|||||1.0|1.0|1.0|1.0|1.0|1.0|■|||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Approval|22|0.2|0.1|0.2||0.2|||||||0.2|0.2|0.2|||||||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Sketches|23||||||||||0.2|||||||||||||■|0.1|0.1|0.1||0.1|||||||||||||0.1|||||||||||||||||||||||||||||||
|Scale Tape Drawings|24|||||||||||||||||||||||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||
|Full Size Tape Drawings|25|||||||||||||||||||||||0.2|0.1|■|0.1||||||||||||||||||||||||||||||||||||||||||||||
|Full Scale Clay Models|26|||||||||||||||||||||||0.2||0.2|■|||||||0.2||||||||0.2|||||||||||||||||||||||||||||||
|Scale Tape Digitized|27||||||||||||||||||||||||0.2|||■|0.1||0.1||||||||||||||||||||||||||||||||||||||||||
|Computer Design Developed|28|||||||||||||||||||||||0.2|0.1|||0.2|■|0.1|0.1|0.1|||||||||||||||||||||||||||||||||||||||||
|Cutter Paths Generated|29||||||||||||||||||||||||||||0.2|■|0.1||||||||||||||||||||||||||||||||||||||||||
|Full Scale Models Milled|30|||||||||||||||||||||||0.1||||||0.2|■|||0.2||||||||0.2|||||||||||||||||||||||||||||||
|Engr Feasibility Evaluation|31||||||||||||||||||||||||||0.1||0.2||0.1|■|||||||||||||||||||||||||||||||||||||||||
|Theme Selection|32||||||||||||||||||||||||||0.2||||0.2||■|0.2||||||||0.2|||||||||||||||||||||||||||||||
|Models Refined by Hand|33||||||||||||||||||||||||||||||||0.2|■||||||||0.2|||||||||||||||||||||||||||||||
|Agile Theme Plan|34||||||||||||||||||||||0.2||||||||||||■|||||0.9|||||||||||||||||||||||||||||||||
|Agile Theme Design|35||||||||||||||||||||||||||||||||||1.0|■||||0.9|||||||||||||||||||||||||||||||||
|Agile Theme Develop|36|||||||||||||||||||||||||||||||||||1.0|■|||0.9|||||||||||||||||||||||||||||||||
|Agile Theme Test|37||||||||||||||||||||||||||||||||||||1.0|■||0.9|||||||||||||||||||||||||||||||||
|Agile Theme Deploy|38|||||||||||||||||||||||||||||||||||||1.0|■|0.9|||||||||||||||||||||||||||||||||
|Agile Theme Review|39||||||||||||||||||||||||||||||||||||||1.0|■|||||||||||||||||||||||||||||||||
|Agile Theme Integration Approva|40||||||||||||||||||||||||||||1.0|||1.0|||1.0|1.0|1.0|1.0|1.0|1.0|■||||||||||||||||||||||||||||||||
|Theme Approval|41||||||||||||||||||||||||||||||||0.2|0.2|||||||0.2|■|||||||||||||||||||||||||||||||
|Eng Part Development|42||||||||||||||||||||||||||||0.2||||||||||||||■|0.1|0.1||||0.2|0.2|0.1|||||||||||0.2|||||||||||
|Feasability Models|43||||||||||||||||||||||||||||||||||||||||||0.2|■|||||0.2||||||||||||||||||||||||
|Structural Analysis|44||||||||||||||||||||||||||||||||||||||||||0.2||■|||||||||||||||||0.2|||||||||||
|Cutter Paths for Ext Surfs|45||||||||||||||||||||||||||||||||||||||||||0.1|||■|0.1|0.2|0.2||||||||||||||||||||||||
|Mill. Stack Foam, Apply Decal|46|||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2|0.2||||||||||||||||||||||||
|Evaluate Verification Model|47||||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2||||||||||||||||||||||||
|Approve Surfaces|48||||||||||||||||||||||||||||||||||||||||||0.1||0.1|||0.2|■|0.1|||||||||||||||||||||||
|Draw Development and Approval|49||||||||||||||||||||||||||||||||||||||||||0.2||||||0.2|■|||||||||||||||||||||||
|Die Process|50|||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.1||||||||||0.2|||||0.2|0.1|||||
|Die Design|51||||||||||||||||||||||||||||||||||||||||||0.2|||||||0.2|0.2|■||0.1||||||||0.2|||||||||||
|Hard Die Cutter Paths Dev'd|52|||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2||||||||0.2|||||||||||
|Die Pattern Developed|53|||||||||||||||||||||||||||||||||||||||||||||||||||0.2||■||||||||0.2|||||||||||
|Agile Eng Plan|54|||||||||||||||||||||||||||||||||||||||||0.2|||||||||||||■|||||0.9|||||||||||||
|Agile Eng Design|55||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■||||0.9|||||||||||||
|Agile Eng Develop|56|||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■|||0.9|||||||||||||
|Agile Eng Test|57||||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■||0.9|||||||||||||
|Agile Eng Deploy|58|||||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■|0.9|||||||||||||
|Agile Eng Review|59||||||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■|||||||||||||
|Agile Eng Integration Approval|60||||||||||||||||||||||||||||||||||||||||||||1.0||||1.0||||||1.0|1.0|1.0|1.0|1.0|1.0|■||||||||||||
|Parts Released|61|||||||||||||||||||||||||||||||||||||||||||||||||||0.2|0.2||||||||0.2|■|||||0.2||||||
|Die Cast|62|||||||||||||||||||||||||||||||||||||||||||||||||||||0.2||||||||0.2|■|0.1|||||||||
|Dies Machined and Constructed|63||||||||||||||||||||||||||||||||||||||||||||||||||||0.2||||||||||0.2|■|0.2||||||||
|Tryout|64|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||||||0.2|
|Soft Tool Development|65||||||||||||||||||||||||||||||||||||||||||0.2|||||||||0.2|0.1|||||||||||||■|0.2||||||
|Soft Tools Proved|66|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■||||||
|Build Program Car|67|||||||||||||||||||||||||||||||||||||||||||||||||||0.1|0.1||||||||||||||0.2|■||0.2|0.2||
|Identify Principal Locating Pts|68||||||||||||||||||||||||||||||||||||||||||0.2||||||||||||||||||||||||||■|0.1|0.1||
|Dies, Constr, Certify Plp Racks|69||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||
|Die & Cut Tools, Guages, Fixt's|70|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.1|0.2|0.1|■|0.2|
|Pilot Operations|71||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|||||0.2|0.2|■|

Figure A-7: Rework Probability Matrix for Cooper's Hybrid Agile-Phase-Gate DSM

|||1|2|3|4|5|6|7|8|9|10|11|12|13|14|15|16|17|18|19|20|21|22|23|24|25|26|27|28|29|30|31|32|33|34|35|36|37|38|39|40|41|42|43|44|45|46|47|48|49|50|51|52|53|54|55|56|57|58|59|60|61|62|63|64|65|66|67|68|69|70|71|
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|Marketing Study|1|■|||||||||||||||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Study and Generation|2|0.2|■|||0.2||||||||0.1|0.2||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Sketches|3|0.1|0.2|■|0.2|0.1|||||||||||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Mgmt Review of Designs|4|0.1|0.1|0.2|■|||0.1|||||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Selection|5||0.2|0.1|0.2|■||0.1||||||0.1|0.2|0.2||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Tape Dwg Generation|6|||0.2||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Model|7|||0.2|0.1|0.1|0.2|■|0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Aerodynamic Tests|8|||||||0.2|■||||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Scale Tape Digitised|9||||||0.2|||■||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Computer Design Development|10|||0.1||||0.1|0.1|0.2|■||0.2||0.1||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Cutter Paths Generated|11||||||||||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
|Full Sim Clay Models Milled|12|||||||||||0.2|■|0.2||||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Engr Preliminary Eval|13|||||||0.1|||0.2||0.1|■|0.1||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Package Approval|14||0.1|||0.2|||||||0.2|0.2|■||||||||0.2||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Plan|15|||||0.2||||||||||■|||||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Design|16|||||||||||||||1.0|■||||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Develop|17||||||||||||||||1.0|■|||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Test|18|||||||||||||||||1.0|■||0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Deploy|19||||||||||||||||||1.0|■|0.9||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Review|20|||||||||||||||||||1.0|■||||||||||||||||||||||||||||||||||||||||||||||||||||
|Agile Concept Integration Approval|21||||||||||1.0|||||1.0|1.0|1.0|1.0|1.0|1.0|■||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Approval|22|0.2|0.1|0.2||0.2|||||||0.2|0.2|0.2|||||||0.2|■||||||||||||||||||||||||||||||||||||||||||||||||||
|Concept Sketches|23||||||||||0.2|||||||||||||■|0.1|0.1|0.1||0.1|||||||||||||0.1||||||||||||||||||||||||||||||
|Scale Tape Drawings|24||||||||||||||||||||||0.2|■|||||||||||||||||||||||||||||||||||||||||||||||
|Full Size Tape Drawings|25||||||||||||||||||||||0.2|0.1|■|0.1|||||||||||||||||||||||||||||||||||||||||||||
|Full Scale Clay Models|26||||||||||||||||||||||0.2||0.2|■|||||||0.2||||||||0.2||||||||||||||||||||||||||||||
|Scale Tape Digitized|27|||||||||||||||||||||||0.2|||■|0.1||0.1|||||||||||||||||||||||||||||||||||||||||
|Computer Design Developed|28||||||||||||||||||||||0.2|0.1|||0.2|■|0.1|0.1|0.1||||||||||||||||||||||||||||||||||||||||
|Cutter Paths Generated|29|||||||||||||||||||||||||||0.2|■|0.1|||||||||||||||||||||||||||||||||||||||||
|Full Scale Models Milled|30||||||||||||||||||||||0.1||||||0.2|■|||0.2||||||||0.2||||||||||||||||||||||||||||||
|Engr Feasibility Evaluation|31|||||||||||||||||||||||||0.1||0.2||0.1|■||||||||||||||||||||||||||||||||||||||||
|Theme Selection|32|||||||||||||||||||||||||0.2||||0.2||■|0.2||||||||0.2||||||||||||||||||||||||||||||
|Models Refined by Hand|33|||||||||||||||||||||||||||||||0.2|■||||||||0.2||||||||||||||||||||||||||||||
|Agile Theme Plan|34|||||||||||||||||||||0.2||||||||||||■|||||0.9||||||||||||||||||||||||||||||||
|Agile Theme Design|35|||||||||||||||||||||||||||||||||1.0|■||||0.9||||||||||||||||||||||||||||||||
|Agile Theme Develop|36||||||||||||||||||||||||||||||||||1.0|■|||0.9||||||||||||||||||||||||||||||||
|Agile Theme Test|37|||||||||||||||||||||||||||||||||||1.0|■||0.9||||||||||||||||||||||||||||||||
|Agile Theme Deploy|38||||||||||||||||||||||||||||||||||||1.0|■|0.9||||||||||||||||||||||||||||||||
|Agile Theme Review|39|||||||||||||||||||||||||||||||||||||1.0|■||||||||||||||||||||||||||||||||
|Agile Theme Integration Approval|40|||||||||||||||||||||||||||1.0|||1.0|||1.0|1.0|1.0|1.0|1.0|1.0|■|||||||||||||||||||||||||||||||
|Theme Approval|41||||||||||||||||||||||||||||||||0.2|0.2||||||0.2|■||||||||||||||||||||||||||||||
|Eng Part Development|42|||||||||||||||||||||||||||0.2||||||||||||||■|0.1|0.1||||0.2|0.2|0.1|||||||||||0.2||||||||||
|Feasability Models|43|||||||||||||||||||||||||||||||||||||||||0.2|■|||||0.2|||||||||||||||||||||||
|Structural Analysis|44|||||||||||||||||||||||||||||||||||||||||0.2||■||||||||||||||||||0.2||||||||||
|Cutter Paths for Ext Surfs|45|||||||||||||||||||||||||||||||||||||||||0.1|||■|0.1|0.2|0.2|||||||||||||||||||||||
|Mill. Stack Foam, Apply Decal|46||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2|0.2|||||||||||||||||||||||
|Evaluate Verification Model|47|||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2|||||||||||||||||||||||
|Approve Surfaces|48|||||||||||||||||||||||||||||||||||||||||0.1||0.1|||0.2|■|0.1||||||||||||||||||||||
|Draw Development and Approval|49|||||||||||||||||||||||||||||||||||||||||0.2|||||0.2|■||||||||||||||||||||||
|Die Process|50|||||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.1||||||||||0.2||||0.2|0.1|||||
|Die Design|51|||||||||||||||||||||||||||||||||||||||||0.2||||||0.2|0.2|■||0.1|||||||0.2||||||||||
|Hard Die Cutter Paths Dev'd|52||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|0.2||||||||0.2||||||||||
|Die Pattern Developed|53||||||||||||||||||||||||||||||||||||||||||||||||||0.2||■||||||||0.2||||||||||
|Agile Eng Plan|54||||||||||||||||||||||||||||||||||||||||0.2|||||||||||||■|||||0.9||||||||||||
|Agile Eng Design|55|||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■||||0.9||||||||||||
|Agile Eng Develop|56||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■|||0.9||||||||||||
|Agile Eng Test|57|||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■||0.9||||||||||||
|Agile Eng Deploy|58||||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■|0.9||||||||||||
|Agile Eng Review|59|||||||||||||||||||||||||||||||||||||||||||||||||||||||||1.0|■||||||||||||
|Agile Eng Integration Approval|60|||||||||||||||||||||||||||||||||||||||||||1.0||||1.0||||||1.0|1.0|1.0|1.0|1.0|1.0|■|||||||||||
|Parts Released|61||||||||||||||||||||||||||||||||||||||||||||||||||0.2|0.2||||||||0.2|■|||||0.2|||||
|Die Cast|62||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|||||||0.2|■|0.1||||||||
|Dies Machined and Constructed|63|||||||||||||||||||||||||||||||||||||||||||||||||||0.2||||||||||0.2|■|0.2|||||||
|Tryout|64||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||||||0.2|
|Soft Tool Development|65|||||||||||||||||||||||||||||||||||||||||0.2||||||||0.2|0.1|||||||||||||■|0.2|||||
|Soft Tools Proved|66||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||||
|Build Program Car|67||||||||||||||||||||||||||||||||||||||||||||||||||0.1|0.1||||||||||||||0.2|■||0.2|0.2||
|Identify Principal Locating Pts|68|||||||||||||||||||||||||||||||||||||||||0.2||||||||||||||||||||||||||■|0.1|0.1||
|Dies, Constr, Certify Plp Racks|69|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|■|||
|Die & Cut Tools, Guages, Fixt's|70|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.1|0.2|0.1||■|0.2|
|Pilot Operations|71||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||0.2|||||0.2|0.2|■|

Figure A-8: Impact Matrix for Cooper's Hybrid Agile-Phase-Gate DSM



| Initial / Original Sequence | Activity Name | Min | Likely | Max | Learning Curve (LC) (between 0 &1) |
|---|---|---|---|---|---|
| 1 | Marketing Study | 1 | 1 | 2 | 0.5 |
| 2 | Package Study and Generation | 2 | 3 | 4 | 0.3 |
| 3 | Concept Sketches | 1 | 1 | 2 | 0.5 |
| 4 | Mgmt Review of Designs | 1 | 1 | 2 | 0.5 |
| 5 | Package Selection | 1 | 1 | 2 | 0.5 |
| 6 | Scale Tape Dwg Generation | 1 | 1 | 2 | 0.5 |
| 7 | Scale Model | 2 | 3 | 4 | 0.3 |
| 8 | Aerodynamic Tests | 2 | 3 | 4 | 0.3 |
| 9 | Scale Tape Digitised | 1 | 1 | 2 | 0.5 |
| 10 | Computer Design Development | 1 | 1 | 2 | 0.5 |
| 11 | Cutter Paths Generated | 1 | 1 | 2 | 0.5 |
| 12 | Full Sim Clay Models Milled | 2 | 3 | 4 | 0.3 |
| 13 | Engr Preliminary Eval | 1 | 1 | 2 | 0.5 |
| 14 | Package Approval | 1 | 1 | 2 | 0.5 |
| 15 | Agile Concept Plan | 0.2 | 0.2 | 0.2 | 1 |
| 16 | Agile Concept Design | 0.4 | 0.4 | 0.4 | 1 |
| 17 | Agile Concept Develop | 0.4 | 0.4 | 0.4 | 1 |
| 18 | Agile Concept Test | 0.2 | 0.2 | 0.2 | 1 |
| 19 | Agile Concept Deploy | 0.2 | 0.2 | 0.2 | 1 |
| 20 | Agile Concept Review | 0.2 | 0.2 | 0.2 | 1 |
| 21 | Agile Concept Integration Approval | 2 | 2 | 3 | 0.5 |
| 22 | Concept Approval | 1 | 1 | 2 | 0.5 |
| 23 | Concept Sketches | 8 | 9 | 11 | 0.7 |
| 24 | Scale Tape Drawings | 3 | 3 | 4 | 0.7 |
| 25 | Full Size Tape Drawings | 3 | 3 | 4 | 0.7 |
| 26 | Full Scale Clay Models | 5 | 6 | 8 | 0.7 |
| 27 | Scale Tape Digitized | 3 | 3 | 4 | 0.7 |
| 28 | Computer Design Developed | 6 | 7 | 9 | 0.7 |
| 29 | Cutter Paths Generated | 3 | 3 | 4 | 0.7 |
| 30 | Full Scale Models Milled | 6 | 7 | 9 | 0.7 |
| 31 | Engr Feasibility Evaluation | 5 | 6 | 8 | 0.7 |
| 32 | Theme Selection | 5 | 6 | 8 | 0.7 |
| 33 | Models Refined by Hand | 5 | 6 | 8 | 0.7 |
| 34 | Agile Theme Plan | 0.2 | 0.2 | 0.2 | 1 |
| 35 | Agile Theme Design | 0.4 | 0.4 | 0.4 | 1 |
| 36 | Agile Theme Develop | 0.4 | 0.4 | 0.4 | 1 |
| 37 | Agile Theme Test | 0.2 | 0.2 | 0.2 | 1 |
| 38 | Agile Theme Deploy | 0.2 | 0.2 | 0.2 | 1 |
| 39 | Agile Theme Review | 0.2 | 0.2 | 0.2 | 1 |
| 40 | Agile Theme Integration Approval | 2 | 2 | 3 | 0.5 |
| 41 | Theme Approval | 3 | 3 | 4 | 0.7 |
| 42 | Eng Part Development | 6 | 7 | 9 | 0.3 |
| 43 | Feasability Models | 3 | 3 | 4 | 0.5 |
| 44 | Structural Analysis | 3 | 3 | 4 | 0.5 |
| 45 | Cutter Paths for Ext Surfs | 3 | 3 | 4 | 0.5 |
| 46 | Mill. Stack Foam, Apply Decal | 3 | 3 | 4 | 0.5 |
| 47 | Evaluate Verification Model | 3 | 3 | 4 | 0.5 |
| 48 | Approve Surfaces | 2 | 2 | 3 | 0.5 |
| 49 | Draw Development and Approval | 3 | 3 | 4 | 0.5 |
| 50 | Die Process | 3 | 3 | 4 | 0.5 |
| 51 | Die Design | 3 | 3 | 4 | 0.5 |
| 52 | Hard Die Cutter Paths Dev'd | 3 | 3 | 4 | 0.5 |
| 53 | Die Pattern Developed | 3 | 3 | 4 | 0.5 |
| 54 | Agile Eng Plan | 0.2 | 0.2 | 0.2 | 1 |
| 55 | Agile Eng Design | 0.4 | 0.4 | 0.4 | 1 |
| 56 | Agile Eng Develop | 0.4 | 0.4 | 0.4 | 1 |
| 57 | Agile Eng Test | 0.2 | 0.2 | 0.2 | 1 |
| 58 | Agile Eng Deploy | 0.2 | 0.2 | 0.2 | 1 |
| 59 | Agile Eng Review | 0.2 | 0.2 | 0.2 | 1 |
| 60 | Agile Eng Integration Approval | 2 | 2 | 3 | 0.5 |
| 61 | Parts Released | 2 | 2 | 3 | 0.5 |
| 62 | Die Cast | 5 | 6 | 7 | 0.4 |
| 63 | Dies Machined and Constructed | 6 | 7 | 9 | 0.3 |
| 64 | Tryout | 3 | 3 | 4 | 0.5 |
| 65 | Soft Tool Development | 5 | 6 | 7 | 0.4 |
| 66 | Soft Tools Proved | 3 | 3 | 4 | 0.5 |
| 67 | Build Program Car | 6 | 7 | 9 | 0.3 |
| 68 | Identify Principal Locating Pts | 2 | 2 | 3 | 0.5 |
| 69 | Dies, Constr, Certify Plp Racks | 3 | 3 | 4 | 0.5 |
| 70 | Die & Cut Tools, Guages, Fixt's | 5 | 6 | 7 | 0.4 |
| 71 | Pilot Operations | 6 | 7 | 9 | 0.5 |

Figure A-9: Activity Duration Data for Cooper's Hybrid Agile-Phase-Gate DSM

# Appendix B

# DSM Excel Macro Instructions

Following is a walk-through on how I used the DSM Excel Macro for my duration analysis. *Note: I was using Office 2019 (V16) on Windows 10. While this macro should work on macOS, this was not tested.* MIT does not offer any digital storage connected with publishing theses. So I have uploaded the Excel sheets with macros I used to a public folder on Microsoft OneDrive:

https://1drv.ms/f/s!AtzwQnKzH0Yng4t2euxrgmLnX0zyGg

I cannot guarantee these files will always be available. If the reader has any questions regarding these files or the contents of this thesis, they are welcome to reach out to me at donmateo@sloan.mit.edu. This email address should forward to my current address until we all are no longer using email.

### Downloading and setting up the Macro

1. Download the DSM Program V2.1 from:

   https://dsmweb.org/excel-macros-for-partitioning-und-simulation/

2. Upoon opening the Excel book, click the 'Enable Content' button that will pop up in a yellow security ribbon to allow the macro to run.

3. Ensure the Visual Basic for Application (VBA) functions for the Analysis Tool-Pak is loaded in your Excel program. This can be checked by going to Excel

Options -> Add-ins and seeing if **Analysis ToolPack - VBA** is listed under Active Application Add-ins. If it is not, find and follow on-line instructions from Microsoft on how to load and activate it.

4. Update the code to correctly call-up the Analysis Toolpack. *This change is because the macro was coded using Microsoft Office 2010. If you downloaded the Excel spreadsheets from my cloud folder, you can skip the below step.*

   - Open up the Visual Basic Editor with Alt + F11
   - In Module 9, Line 233, add an **'M'** to *.XLA*. The beginning of the line should now read:

     *Application.Run "ATPVBAEN.XLA*M*!Histogram"*
   - If you do not make this change now, the simulation will fail to run after you enter the impact matrix at the end of this tutorial. However, Excel will then prompt you to debug the code, open up the Visual Basic Editor, and take you exactly to this line where you can make and save the change.

### Entering the element data into the *Element Info* sheet

1. Add or delete rows as needed that include columns A thru E.
2. Add names of elements to Column B and short names and comments if desired to Columnn C and D.
3. Per the note in A1, delete all red numbers in Column A. They will be repopulated by the macro.
4. Reset Completion Levels in Column E to 0% if you are looking to simulate the PDP from the start.
5. Click the 'Update DSM' button in G1.

### Entering dependencies into the *DSM* sheet

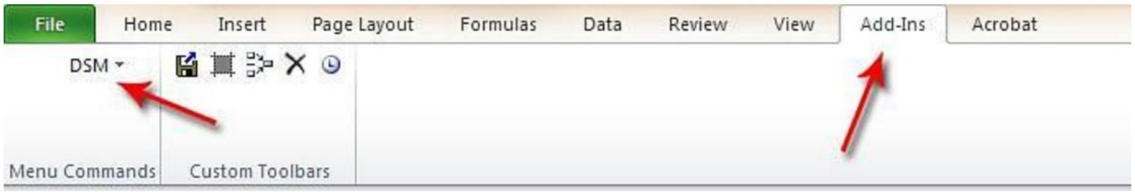


Figure B-1: Location of DSM toolbar

1. Per Section 5.1, enter dependencies by inputting a **1** in relevant cells using the Inputs in Row (IR) convention to include feedback.

2. In the 'Add-ins' toolbar at the top, click the DSM pull-down menu (See Figure B-1) and then click the 'Generate dependence report' command.

### Entering activity data into the *SIM Input* sheet

*Since we are not using DSM theory to alter the sequence of events, we will not be using the Partitioned DSM or Banded DSM sheets. If you use the Partition DSM command, the macro will re-order the sequence of events based on an optimization algorithm as briefly mentioned in Section 5.1. If you are trying to simulate the PDP using the given sequence, you will have to close the Excel sheet and restart from the 'Update DSM' step in the Element Info section.*

1. Click the 'Simulate DSM' command in the DSM pull-down menu. *If you have updated the DSM recently, you need to start the simulation steps through the pull-down menu to update the elements on this sheet with the ones in your DSM. If that is not the case, you can start a simulation just be navigating to the Sim Input sheet and going to step 2.*

2. Click the 'Clear Data' button at the top of the sheet if required.

3. Read the notes on the sheet to enter the desired Time Step size, the Collect Data option, and desired number of runs.

4. Fill in the Min, Likely, Max, and Learning Curve values of each activity.

5. Click the 'Accept Data Below' button in red at the top.

### Entering probability of rework into the *Probability* sheet

1. Click the ‘Clear Data‘ button at the top of the sheet. *Anytime you update the DSM, you will need to clear the data to reset the highlighted cells to the correct positions.*

2. Per the information in Section 5.2, enter the probability data manually into each highlighted cell.

3. Click the ‘Accept Rework Probabilities’.

### Entering impact data into the *Impact* sheet

1. Click the ‘Clear Data‘ button at the top of the sheet. *As in the previous step, anytime you update the DSM, you will need to clear the data to reset the highlighted cells to the correct positions.*

2. Per the information in Section 5.2, enter the impact data manually into each highlighted cell.

3. Click the ‘Accept Rework Probabilities’.

### Looking at the *Sim Results* sheet

*After some computing time, the macro should send you to the* Sim Reults *sheet. If you get an error that is not related to the Analysis ToolPak as mentioned before, confirm you only have one Excel Worksheet with the DSM Macro open. Closing all workbooks, reopening the one you want to run, and then going through the above steps in order again should fix most problems. Whether or not you have an error, before you close the workbook, be sure to follow the below underlined note regarding copying inputs to save you time.*

It is a good idea at this point to copy all the data you entered into another workbook that does not contain the DSM Macro. This will prevent you from having to manually re-enter large matrices over and over again each time you run or modify the DSM. Good things to copy are:

1. Element Full Name and Abbreviations

2. The DSM Matrix

3. The min, likely, max, and LC value of each activity

4. The probability of rework matrix

5. The impact matrix

In my cloud drive, you will see a complimentary *Data* workbook for each DSM macro workbook where I have copied the above data into separate sheets. When copying back into the DSM macro workbook, use the ‘paste values’ option.

The Sim Results sheet will be presented with run # in Column A and the simulated length in time steps in Column B. The bin and frequency table with the Histogram show the distribution for the first 100 runs as described in Section 5.3. I added two cells to my Excel files that calculated the median and standard deviation of all the runs simulated.

In the *Single Run Data* sheet, if you enabled that option on the *Sim Input* step, you can see the progress of each activity at each time step for a random run. This can be used to get insight into how iteration loops are actually happening in your PDP by seeing when progress for an activity resets and how often it gets completed.

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