17th Annual
Engineering
Project
Organization
Conference

Working Paper Proceedings

Scenario-Based Flexible Manufacturing Facility Designs: Understanding Lifecycle Value

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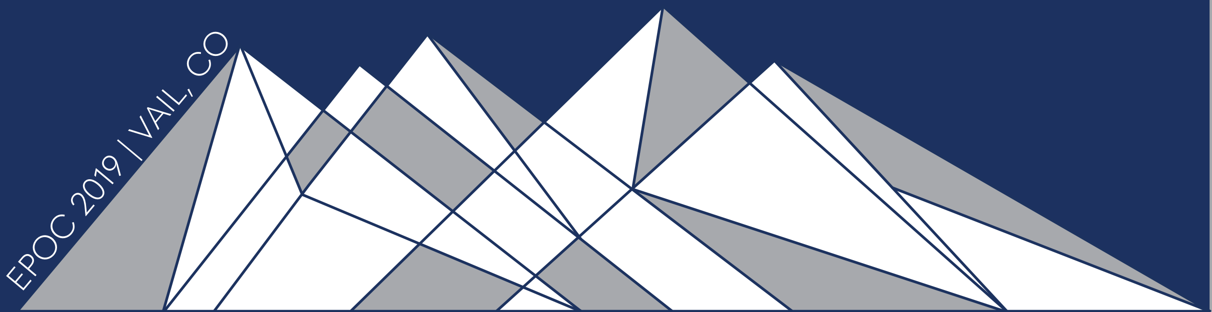

SCENARIO-BASED FLEXIBLE MANUFACTURING FACILITY DESIGNS: UNDERSTANDING LIFECYCLE VALUE

ABSTRACT

Across the U.S., there is an increasing supply of dormant or obsolete buildings, which have surpassed their useful life. In the manufacturing sector, the rate of facility obsolescence is especially high. Because the facilities in this sector are typically customized for a specific product or process, they struggle to accommodate rapid evolution in product families over their lifetime. While including flexibility into the design of a manufacturing facility can increase its ability to respond to change, the additional capital investment can be difficult for many owners to conceptualize and justify. For this reason, we present three potential front-end facility design strategies—dedicated, scalable and general purpose—as scenarios to explore a capital investment model. Two case studies, representing the highest and lowest investment scenarios, are used to investigate both the expected and unexpected realization of uncertainties, along with the facility's ability to accommodate the actual changes. This research shows that, when uncertainty is realized, general purpose facilities offer the owner the lowest, long-term capital investment. Ultimately, however, this paper is limited by its consideration of uncertainty deterministically and thus proposes a path forward for future research.

KEYWORDS

Front-end planning, lifecycle planning, cost model, uncertainty, facility design strategies

INTRODUCTION

Across the U.S., there is an increasing supply of dormant or obsolete buildings, which have surpassed their useful life and no longer have the capacity to meet the evolving demands that are placed on them (Seely 1972, Johnson 1996). Over time, these obsolete facilities become dormant and eventually negatively affect the health, safety, and welfare of local citizens (Mallach 2006). Simultaneously, additional resources are extracted to construct new buildings that meets emerging demands. In the manufacturing sector, the rate of facility obsolescence is especially high. For manufacturing facilities, unplanned or unpredictable changes in consumer demand, facility requirements, and regulatory restrictions can cause a facility to become prematurely obsolete (Seeley 1972, Maslak et al. 2018). The implementation of Industry 4.0, or the digitization of cyber-physical systems, in recent years has also increased the rate of change in manufacturing facilities. Therefore, there is a need for these facilities to accommodate substantially more change over their lifetime to avoid obsolescence.

As identified in the Engineering Project Organization's Grand Challenges, future research should address and improve systems integration and lifecycle governance of facilities, which includes those facilities operating within the manufacturing sector (Sakhari et al. 2017). According to Sakhari et al. (2017), Grand Challenge 4: Systems

Integration is driven by social well-being, complexity and uncertainty, across an array of research areas, including disciplinary integration and coordination, contingent decentralized decision-making, and front-end planning and shaping. This research specifically addresses Grand Challenge 4 by striving to improve a manufacturing organization's decision-making capabilities with the intent of reducing premature facility obsolescence. By strategically improving initial facility planning and considering the lifecycle of the facility, the manufacturing sector itself can reduce the overall environmental impact and the long-term social consequences of facility vacancy.

One method of extending the useful life and capabilities of these facilities is to incorporate flexibility into the initial facility design. According to Upton (1994), flexibility is defined as "the ability to change or react with little penalty time, effort, cost or performance." A facility can be flexible in many ways. The interior space may be reconfigurable; utilities relocatable; and the site adapatable. Flexibility allows the project owner to accommodate an array of potential uses that may occur, both in the present and throughout the facility's lifetime (Pagell et al. 2000, Ross et al. 2008). However, the inclusion of flexibility is difficult for many owners to justify. Flexibility is typically perceived as requiring greater capital investment during the construction phase, which is at odds with initial cost decisions, such as net present value (NPV) or return on investment (ROI). Furthermore, there is no guarantee that the envisioned change will occur. As such, there is a high potential that the capital invested for flexibility will not offer the owner the long-term benefits that were originally intended.

The goal of this research is to improve a manufacturing organization's ability to effectively conceptualize and employ flexible facility design strategies when faced with uncertainty. In this research, we identify three potential design decisions that an organization can make during the front-end development process of a manufacturing facility. Each of these early design decisions, which are presented as scenarios, has the potential to offer the owner value, either in the short- or long-term. However, due to the inherent nature of uncertainty, there is no guarantee this value will be obtained (Gaimon and Singhal 1992). For this reason, there is a need to understand how each scenario can accommodate uncertainty, along with the impact of pursuing that design. Scenario-based facility designs are beneficial because they have the potential to create insight about the long-term effects of initial design decisions (Schnaars 1983, Galle et al. 2017). For the purposes of this paper, this impact is discussed in terms of capital investment to provide a tangible unit associated with each decision. This paper develops an understanding of the drivers of change throughout a manufacturing facility's lifetime and how each scenario can accommodate changes. As the reader will observe, the inclusion of flexibility is not a one-to-one relationship with uncertainty, but rather a combination of design decisions that provides a buffer against a range of uncertainty over the lifetime of the facility.

THE CHALLENGES OF EARLY PROJECT DEFINITION

Under the traditional design-bid-build construction method, the owner is solely responsible for the inception, feasibility, and scope of the project, which includes the intended end-use of the building. The engineer then responds to owner requests with a design that supports the identified scope. Projects generally fail due to the inability of owners to properly define their scope (Cho and Gibson 2001). To address this problem, research on construction scope definition has primarily been centered around a Construction Industry Institute (CII) tool called the Product Definition Rating Index (PDRI), which was developed in 1996 (Dumont et al. 1997, Gibson et al. 2000, Tih-Ju et al. 2014). The PDRI is useful because it brings team members together to improve project initiation, scope planning, scope definition, and scope verification (Cho and Gibson 2001). However, while the PDRI successfully brings team members together, it does not facilitate the even earlier conceptual, pre-project planning discussions that are required to consider both the current *and the future use* of the facility and thus does not intentionally enhance the building's lifecycle.

In order to consider both the current and future use of the facility, an array of short- and long-term uncertainties must be considered during project initiation. Over time, as the project is initialized and the design progresses, these uncertainties become more defined, thus reducing variability. This can be represented with the traditional cone of uncertainty shown in Figure 1 (McConnell 2006, Antunes and Gonzalez 2015). Successful project development depends on the team's early ability to accurately predict, quantify, and accommodate uncertainty throughout the entire facility's lifetime. Traditionally, once the facility is fully designed and constructed, the variability in uncertainty for the project, including cost, schedule and project requirements, are considered to be resolved (Antunes and Gonzalez 2015). At this point, the owner has near complete knowledge about all components of the projects and has a facility that meets their precise needs at that moment in time. As time progresses and the facility enters the operations phase, changes driven by the consumer environment begin impacting the facility. Both new and re-occurring uncertainties then begin to increase as the facility continues to operate. The increase in uncertainty over time is also represented in Figure 1. The capacity of the facility to withstand these uncertainties, which are discussed in the next section, is paramount for it to continue its useful life.

SOURCES OF UNCERTAINTY

In order for project teams and facility owners to accommodate uncertainty over the lifetime of the facility, there is a need to understand the timing and impacts of uncertainty and the changes each creates. Under ideal circumstances, the amount and type of flexibility incorporated into the facility would precisely accommodate the need for future changes. In doing so, the owner could optimize their investment, while simultaneously ensuring the facility never becomes the limiting factor when changes occur. In reality, this is difficult to achieve because the future of these facilities is uncertain and specific changes are not guaranteed to occur. If the change does not occur, or if the change is outside of the planned-for parameters, the facility will require renovation or modernization.

In their research, Maslak et al. (2018) directly and indirectly suggested the four primary drivers of change in industrial facilities but did not necessarily consider each type of uncertainty's unique impacts on the facility over time. These uncertainties include changes in the product, manufacturing process and market demand.

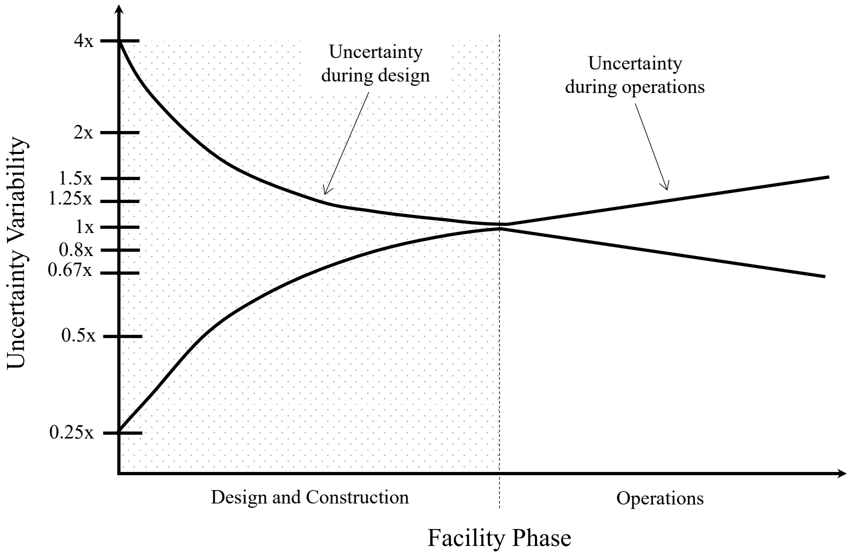

Figure 1. Uncertainty surrounding facility development and operations

REGULATORY AND PRODUCT UNCERTAINTIES

In the manufacturing environment, product uncertainty is crucial to facility planning. Typically, a new facility is developed for the purpose of bringing a new product to market. Because facilities have long-lead times, and early entry into emerging markets offers significant profit margins (Slater 1993), many facility owners must begin the facility development simultaneous with product development. This necessitates that facility design begins even prior to complete knowledge of the product characteristics (Maslak et al. 2018). In doing so, the facility design can be completed at the same time, or shortly after, the product receives its final approvals. These approvals stem from both internal and external organizations, including regulatory agencies (e.g., Food and Drug Administration or Environmental Protection Agency). Some sectors are particularly stymied by their governing agencies. For example, in the pharmaceutical sector, only 9.6% of conceptualized product reach final approvals (Thomas et al. n.d.). Thus, for companies working in this sector, along with similar sectors, there is very real possibility that the intended product will not be manufactured within the facility by the time construction is completed, but rather, a different product being developed in parallel will take its place.

Even after construction, product uncertainty continues throughout the lifetime of the facility. Although the facility may begin manufacturing one product, there is no guarantee that it will continue to be produced over the entire life of the facility. Product turnover is often driven by organizational decisions, including the need for strategic portfolio management, which requires both maintaining diversity and removing or replacing products that do not provide the required profit margins (Figueiredo and Kyle 2006). These changes typically occur over time and are a result of evolving demand and technologies (Adner and Levinthal 2001). Thus, for facilities that experience product uncertainty, there is a need to ensure the facility can accommodate a variety of potential products.

PROCESS

Accompanying every product is a specialized manufacturing process, which is installed within the facility. This process may be a continuous assembly-line operation, where multiple machines are connected via a conveyer system, a batch process that moves a fixed group of products through all stages of production, or even a job shop model, which processes a small number of products at a time. According to Utterback and Abernathy (1975), process innovation follows product innovation. For this reason, during early facility design, the process may not be finalized. Furthermore, in the midst of Industry 4.0, which is considered the next industrial revolution, these processes are evolving rapidly. This evolution includes increased automation, digitization and networking, and cyber-physical systems, which the facility must be able to readily accommodate (Lasi et al. 2014). This creates a risk that the constructed facility may be inadequate for its sole purpose of housing the manufacturing process and associated product. One method that owners have used to reduce the risk of late product definition is the implementation of adaptable and flexible manufacturing systems (Zhang et al. 2006). However, Maslak et al. (2018) noted that such systems also have the potential to impact the facility's structural, mechanical and electrical systems and their range flexibility must be considered during the facility design. In many cases, when early process definition is not possible, the facility design mandates a significantly different approach to accommodate the potential changes to the process, such as the inclusion of flexibility.

DEMAND

Uncertainty in product demand is driven by an evolving consumer market. Facilities are designed and constructed to support the production of a specified quantity of products. However, early in the design process, the quantity of product needed can be challenging for many owners to predict. Furthermore, this demand fluctuates over time and is dependent on the product that is being produced (Figueiredo and Kyle 2006). Previous research has focused on how demand changes, particularly demand increases, can be accommodated by the process (see: Sahinidis & Grossmann 1991, Gupta and Maranas 2003) or the addition of new facilities at the various sites (see: Tsiakis et al. 2001, Cardin et al. 2015). However limited research has been performed on how to appropriately accommodate a potentially wide-range of capacities within a single facility design. If demand oscillates too much above or below the predicted, modifications to the facility are typically required. Thus, if an owner wishes to begin developing the facility, the desired capacity must be defined early. This uncertainty results in a risk that the manufacturing facility could be undersized, leaving the owner to weigh lost revenue from unmet demand against the investment cost for renovation or a new facility.

SCENARIO-BASED CAPITAL INVESTMENT MODEL FOR FLEXIBLE FACILITIES

If the facility owner considers flexibility during early in the design process, then the facility can respond to limited a range of uncertainty throughout the facility's lifetime. Once the changes driven by uncertainty exceed that which the facility can accommodate, then a change or renovation to the facility itself must occur. A facility will eventually reach the end of its useful life either due to age or due to obsolescence, where the facility can no longer accommodate the changes demanded of it (Seely 1972, Langston 2008). The challenge, therefore, is to strategically determine the amount and type of uncertainty the owner wishes to accommodate within the facility early in the design process, alongside the investment they are willing to make to ensure the facility's longevity. This is complicated by a need to understand and justify alternative, potentially more capital-intensive flexible facility designs early in the design process.

Scenario-based thinking provides a setting for the exploration of the future. While popular in business, scenario-based planning has been less utilized in building design and development (Galle et al. 2017). The development of scenarios improves long-term forecasting methods when faced with uncertainties (Schnaars 1987). Unlike forecasts, however, scenarios do not strive to find the most likely path to the future (Pillkahn 2008). Instead, scenarios provide a suite of potential options for an organization to extensively consider. Scenario-based thinking requires two major components: First, scenarios must provide a qualitative and descriptive narrative of how the future is predicted to unfold; Second, these scenarios must include the development and exploration of a set of plausible features that could be, but do not have to be, incorporated to accommodate that future (Schnaars 1987).

In their paper, Maslak et al. (in review) indicated that there was no one-size-fits-all approach for incorporating flexibility to accommodate this uncertainty. Instead, a cluster analysis of design features identified in case studies was used to derive three overarching strategies guiding the development of a flexible manufacturing facility. These strategies included dedicated, scalable, and general purpose facilities. In other words, during early facility planning, the owner has three potential options to address flexibility: (1) build the facility as *dedicated*, such that the facility is precisely designed around a known product and manufacturing process with a very minor ability to change; (2) build the facility as *scalable,* such that some changes in the manufacturing process or product demand can be accommodated by the facility, or (3) build the facility as *general purpose*, such that significant changes in the manufacturing process or product demand can be accommodated by the facility. These strategies form the basis of the scenarios explored in our research:

- *Dedicated facilities* are employed when a single product family is identified. These facilities are optimized around that product family's manufacturing process, thus requiring the least initial resource investment. Minor design choices, such as increasing column bay spacing, increasing height, and strategically routing utilities can be employed to allow these facilities to accommodate minor changes. The facility can then be used until the design life of the facility is reached, as long as the product family's characteristics (e.g., design parameters or number of variants) and demand profile remain relatively constant. The cost of refitting the facility is high and requires significant renovations because the facility itself is so tailored to the single product family. These facilities will become obsolete when the product family's characteristics changes significantly or market demand decreases sharply, which typically leads to demolition and replacement with a new facility.

- *Scalable facilities* typically require slightly more resources during the initial design and construction to accommodate future changes in the facility. These designs are characterized by the incorporation of a small amount of additional floor space, modular production areas and pre-investment in oversized utilities. They typically incorporate the minimum amount of equipment needed to meet known short-term demand, but retained the ability to rapidly increase production capacity if needed. By incorporating additional resources to accommodate more demands than are initially placed on the facility, a buffer against obsolescence is created. When a change occurs, and new demands are placed on the facility, less resources must be invested to accommodate the change. This is because neither complete renovation, nor reconstruction, is required. Instead, only moderate adaptations must be implemented. Furthermore, because these facilities are expanded incrementally, moderate changes in the product or process can be accommodated during each incremental growth period.
- *General purpose facilities* require resources substantially above and beyond the other two strategies. These facilities typically have a pre-investment in foundations and a much larger square footage of additional floor space, along with a plan to transition that space into functional areas as needed. Typically, these facilities require the greatest initial capital investment. However, this type of facility is well-designed to respond to high uncertainty in the manufacturing process and reliable increases in product demand. Furthermore, the investments made in the facility enable it to readily accommodate changes in the product family. Thus, when a change occurs, these facilities have the greatest ability to accommodate it with the least additional resource investment.

Each of these scenarios impacts the facility owner’s lifetime capital investment, as seen in Figure 2. Because dedicated facilities are designed to accommodate a very specific product and manufacturing process, the initial investment is lowest. Thus, from inception to operations (the design and construction phases in Figure 2) owners are only paying for a design that strictly accommodates their known needs. Conversely, scalable facilities require slightly higher investment to allow for the incremental growth of product and processes. These facilities are ideal for owners who expect growth in the long-term but are unwilling to invest in initially. General purpose facilities, on the other hand, have substantially higher initial investments because these facilities are planned for the long-term and when uncertainty is high. The excess material and design components result in a notably higher initial investment for the owner and a slightly longer construction time.

After the design and construction phase, the facility will then operate over a period of time until it reaches the end of its first useful life (beginning of renovations in Figure 2) at which point new demands necessitate change within the facility. Note that the operational time for each of these scenarios is considered to end at the same time. Although these changes can occur on varying on scale, for the purposes of this model, we assume the change is substantial enough to bring the facility to the end of its first useful life. At this point, the facility must be renovated or be removed from service. For dedicated facilities, this change may be small, such as a growth of product demand or the incorporation of new equipment technology. When such change occurs, the facility's design typically does not have the capacity to accommodate it and significant renovation, or even complete reconstruction, is necessary. When this same type of changes occurs within scalable facilities, however, only mild renovations may be required. These renovations may include tasks such as fitting out surplus space, adding more utilities and/or purchasing new equipment. Conversely, general purpose facilities, which were initially pre-invested in, can readily accommodate these changes. Once the change has been performed, the facility can begin its operations once again (second operations phase in Figure 2). The time it takes to renovate dedicated facilities is significantly longer than the time it takes to renovate scalable or general purpose facilities. Therefore, scalable and general purpose facilities have an earlier start to their operational time, Δ_{OT}, which has value to the owner as the new product will have a shorter time to market. In addition, we theorize a difference in capital investment across the facility strategies. Represented by Δ_{CI}, the value in scalable and general purpose designs becomes apparent after the first significant change is needed. Once renovations have been completed, and the facility operates for a period of time, a new change will eventually take place, which the facility must accommodate or risk obsolescence. This second change is beyond the scope of this paper, but should follow a similar pattern.

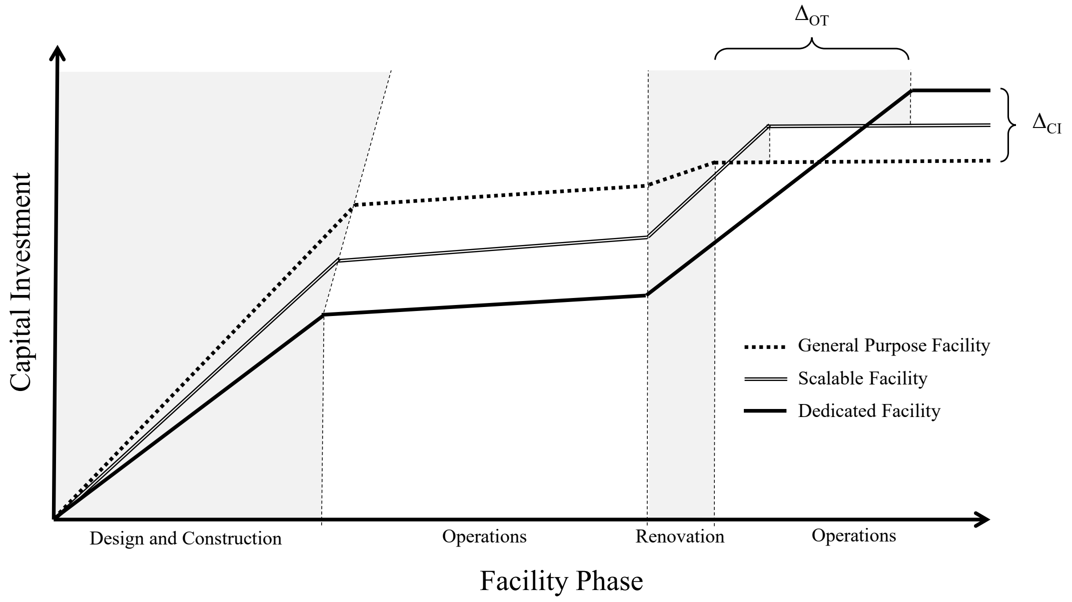

Figure 2. Theoretical capital investment in manufacturing facilities over time

RESEARCH METHODS

According to this model, if the owner accurately incorporated flexibility in the design, then the owner has reduced their capital investment in the future. Thus, here is a need to confirm that each scenario can offer the owner the expected long-term value throughout two useful lives. To do so, we review case study evidence of both extremes in the model, a dedicated and general purpose facility, to establish if the actual investment followed a similar path to that of the theoretical investment model, when subjected to uncertainty. The use of case studies enables us to perform exploratory research by tracing actions over time (Yin 1984). These case studies were collected as part of a larger research project where the topic of facility flexibility was explored following Yin's (2017) case study procedures. For the purposes of acquiring data, a flexible facility was defined as a facility that supports a cluster of products and manufacturing processes to reduce time-to-market and anticipate changes in future manufacturing needs at optimal cost. Within these case studies, we explored the accumulated effect of uncertainty on the manufacturing facility's lifecycle. This included the consideration of uncertainty during facility design and development, through operations and subsequent renovations.

These case studies were performed through semi-structured interviews with facility owners, engineers, and contractors. Semi-structured interviews allowed the team to explore the case with a general list of questions that are neither structured in a specific order, nor mandated (Oppenheim 1992). This method allowed the team to identify and explore the unique attributes of each case study as well develop an understanding of cause-effect relationships stemming from uncertainty. As suggested by Taylor et al. (2011), the research team was careful to maintain validity and documented and summarized each case. Once these case findings were completed, we then submitted it to the participants for verification and accuracy. These findings were then analyzed and input into an excel-based spreadsheet to maintain data consistency across the cases.

Because this research is constructed from a previous understanding of each facility design, both of the case studies presented here have already been pre-aligned into a scenario. In previous research, a clustering analysis of design features grouped the first case study into the dedicated facility design category and the second case study into the general purpose design strategy (Maslak et al. 2018). However, as the reader will observe, the design features associated with each facility both encompass and exceed the features of their respective scenario descriptions. Furthermore, at the time of data collection, the capital investment model had not been developed. Thus, the life of these cases are presented and compared as evidence to confirm the underlying theory. Although the data was collected based on Yin (2017), the analysis in this paper more closely follows Stake (1995), in which direct interpretation is employed to understand the underlying themes.

RESULTS

CASE 1: DEDICATED FACILITY

The owner in this case needed to rapidly construct a temporary expansion to a manufacturing facility to meet a backlog of demand for their alternative energy generation products. These products are large components of wind turbine equipment needed for harnessing wind energy and converting that energy into electrical power. The facility expansion needed to accommodate the large size of turbine blades (approximately 100-feet) and tower components, as well as a known job shop production process that established 'stations' to complete each of these products. With knowledge of the precise product characteristics, a known process, and a stable backlog of orders, the owner prioritized getting the facility expansion operational as quickly as possible. Only equipment and space needs that were immediately necessary for current operations were included in the facility design. Due to the large size of the products, the entire $12-million facility ($192 per square foot) was dedicated to the manufacturing process, with the goal of doubling their existing manufacturing capacity. The resulting facility was an expansive 62,500 square-foot canvas tent structure, completed in only 30-days, after site preparation, installation of underground utilities and pouring of the concrete foundation system.

Once operational, this facility had a short first useful life. Two oversights in the manufacturing process mandated immediate and significant renovation. First, the shape and height of canvas tent structure had to be adjusted to allow products to move between stations. Second, several stages in the manufacturing process used precision lasers which were highly sensitive to movement. Because of canvas tent was supported by a light aluminium frame, the facility was vulnerable to vibrations caused by the wind and a costly reinforcement of the frames was needed. After making these renovations, the dedicated facility served the owner well for several years. Continually increasing demand ultimately lead this facility to become a permeant structure. However, over time, new product variants were created that were both longer in length and made of composite materials that have new process requirements. As a result, the facility has undergone over significant renovations and countless minor modifications over the past 10 years.

CASE 2: GENERAL PURPOSE FACILITY

The owner in this case was seeking to expand their operations to keep up with predicted demand for an aluminum beverage bottle. This predicted demand growth was expected to occur in emerging markets both within and outside the U.S. and coincided with owner's marketing team 'price promoting' the new aluminum bottles by offering the product at a reduced price. Based on their forecasts, the owner wanted the facility operational as rapidly as possible. However, as much of the demand was still only forecasted and had not completely materialized, the continuous manufacturing line was built to minimum capacity of 1,200 bottles per minute, with the intent to expand the lines to a capacity of 1,800 bottles per minute in the near future. Because of the forecasts, this owner was willing construct an approximately $170-million ($1,700 per square-foot, including equipment) general purpose facility, which included pre-investment in additional footings for future machines, unused square-footage of floor space and the strategic oversizing of mechanical and electrical utilities in order to ramp up operations. Utilities that could be installed modularly, such as vacuum pumps, were designed to the minimum production capacity of 1,200 bottles per minute. Conversely, those that could not be quickly and cost-effectively changed, or those that may impact current production for an extended period of time if replaced, such as chillers and heat exchangers, were installed for the maximum capacity. In doing so, minimum operational downtime would be required when the facility was fitted out to achieve the higher production capacity. This capital investment strategy complied with the owner's requirement for a three-year return on investment. After 16 months from concept to final completion, the 100,000 square-foot facility became operational.

When the owner's marketing team discontinued the price promotion, consumer demand dropped dramatically, as customers were not willing to pay more for the product. At the same time, demand for the product in emerging markets also softened.

Each of these demand shifts occurred within the first year of the facility's operational life and both were unexpected, as they diverged from all forecasts prepared during facility development. Thus, the owner was forced to make a decision: cease operations of this facility and discontinue its use, or refit the facility to produce a different product. The owner chose to invest an additional $17 million, or 10% the cost of the initial facility, in manufacturing equipment that allowed the facility to produce aluminium cans, in addition to the aluminium bottles. However, only a few pieces of new machinery needed the additional footings and the extra square-footage of floor space was ultimately used for storage of maintenance parts and completed product, rather than being converted to production space. As a result, the facility can now switch between the products as needed to meet demand with only four days of downtime.

DISCUSSION AND LIMITATIONS

In each of these two cases, the owner had the option to either (1) design the facility for exactly what they needed or (2) design the facility for what they predicted they may need in the future. In the first case, the owner designed a dedicated, canvas tent structure around known product and process specifications due to a perceived urgency to make the facility operational as quickly as possible. This strategy, which was intended to be temporary, allowed the owner to obtain the desired time-to-market, but ultimately constrained the owner for future changes in the long-term. Furthermore, early in operations two initial, minor design oversights required significant capital investment to adapt the facility's structure. Over time, increasing demand growth mandated the continued use of this facility. Because this facility was specifically designed around pre-defined, existing requirements, long-term product and process changes continually require downtime and additional capital. This relationship is consistent with our expectations and the theoretical model (see Figure 2).

A key lesson from the dedicated facility case study is identifying the importance of aligning the long-term product life with the facility lifetime. For products with a short production window or expected period of demand, a disposable building may be the best strategy. During facility development, the owner in this case was unsure of whether the market for wind power would be sustained in the absence of government subsidies and was reluctant to commit to a more permanent manufacturing facility. However, as evidenced in this case, an overly customized facility can become a burden on capital investment if demand remains strong for long enough and product families evolve with that demand.

The owner in second case study also had a perceived an urgency to bring the facility to market as rapidly as possible because current operations were not adequate to keep up with forecasted increase in demand. In contrast to the first case, however, this owner planned for the longer-term and constructed a general purpose facility. Doing so required slightly more construction time and initial capital investment, but provided the owner with the opportunity to meet predicted, rising demand. Strategic design choices, such as additional footings, surplus floor space, and a combination of modular and oversized utilities, simultaneously allowed the owner rapidly increase production and reduce downtime during changes, which was expected to offset the higher initial investment required. Ultimately, however, the uncertainty for which the owner pre-invested capital was never realized during our observational period. Instead, the owner was able leverage the general purpose facility design to change from aluminium bottles to aluminium can with little additional investment. However, as the owner continues to revise their products, there is a possibility that consumer demand for aluminium bottles may increase if the price premium is reduced.

A key lesson from this case was that, when planning around uncertainty in demand, all options should be considered. This facility was designed to satisfy both the current demand and an expected increase, but no plan was in place to adapt to a decrease in demand. If owners expect a decrease in demand, then the facility will simply not be built. Thus, at a minimum, the expected demand must be positive. This does not, however, preclude the possibility of experiencing a temporary contraction in the demand of one product in the product family. The use of a strategic flexible design ultimately enabled the owner to accommodate a range of unforeseen changes.

The use of scenario-based thinking would have offered these manufacturing facility owners the ability to consider their capital investments based on assumptions around the uncertainty associated with the product. By understanding each scenario during design, the owner could have reviewed their understanding of the uncertainty and strategically determine the best facility type for their needs. For example, the owner that built a dedicated wind turbine facility may have preferred a scalable design, which allows for some flexibility to accommodate changes in their product size. This would have been well-suited for an owner that works in an industry with such a fast evolution of technology and materials. By strategically investing in facilities that meet a company's long-term needs, instead of selecting the lowest initial investment, owners can extend the useful life of their facilities. However, even the strategic adoption of a flexible design strategy does not guarantee that the facility has the necessary responsiveness for the future changes it will ultimately have to accommodate. For this reason, the value of these facilities cannot be considered deterministically because there is not a one-to-one relationship between the facility design and the array of uncertainties. The owner that build a general purpose aluminum bottle facility illustrates this point. Despite having a high confidence in their demand forecasts, the market did not develop according to those forecasts.

CONCLUSION

This research explored the need for flexibility in manufacturing facilities by considering an array of uncertainties, including product, process, and demand, that begin during early during design and continue throughout the operations phase. Three flexible facility design strategies were presented as scenarios to describe a means of responding to this uncertainty and reducing potential facility obsolescence. A framework was presented to describe the performance of each scenario based on initial capital investment. *Dedicated facilities*, which represent the lowest cost and least flexible design option, are optimized around a specific product and process. Selective and strategic implementation of design components can enable these facilities to accommodate minor changes. However, when larger changes occur, these facilities do not readily have the ability to accommodate them and require significant investment over their lifetime. *Scalable facilities*, which have an array of potential initial investments, represent the middle class of flexible facilities. Strategic design for expansion allows these facilities to efficiently adapt to some product and process changes over time. Finally, *general purpose facilities*, which represent the greatest capital investment, have the greatest potential to adapt over time with minimal additional investment. These facilities retain the capacity to rapidly adjust to the realization of dynamic uncertainties throughout their entire lifetime. When a change occurs, the component systems in the facility typically have the capacity to accommodate it, with minimal need for additional investment.

We then discussed two specific cases with differing design strategies and described how they responded to changes over time to determine the validity of our framework. These facilities exemplified dedicated and general purpose scenarios, which were the most extreme capital investments in our framework. In the first case, a wind turbine owner constructed a dedicated, canvas-tent structure to meet a high backlog of demand. This design strategy was chosen because it offered the owner the most rapid time to market. After construction, the owner discovered demand was continuing to grow and, after a series of costly modifications to make the facility viable, ultimately decided to make it a permanent structure. Over time, this highly customized facility was forced to accommodate a series of minor product and process upgrades, at a significant investment. In contrast, the owner in the second case constructed a general purpose facility in anticipation of a large increase market demand. This facility included pre-investment in footings, space, and utilities for equipment that was not yet purchased. Doing so would, in theory, allow the facility to rapidly accommodate demand growth. However, the predicted growth did not manifest and the owner was left with facility that was overdesigned for their needs. Ultimately, use of this design approach, along with an additional investment in new equipment, allowed the owner to efficiently repurpose the space for a different product.

As we can see from the two cases, strategic, well-intended facility investments did not always offer the expected long-term return. In neither case did the owner successfully predict and accommodate the future state of their operations or the market. This suggests that a deterministic approach for accommodating uncertainty in facilities is not the complete solution. The use of a stochastic model could better accommodate the range of uncertainties and facility impacts that may occur. While using flexibility to avoid obsolescence is a noble goal, unless uncertainty is considered stochastically, it is unlikely that these flexible design approaches can be successfully aligned with the long-term needs of owners. Furthermore, these three scenarios lend themselves well to an option-based financial analysis, such as real options.

REFERENCES

Adner, R., & Levinthal, D. (2001). Demand Heterogeneity and Technology Evolution: Implications for Product and Process Innovation. *Management Science*, 47(5), 611–628.

Antunes, R., & Gonzalez, V. (2015). A Production Model for Construction: A Theoretical Framework. *Buildings*, 5(1), 209–228.

Cardin, M.A., Ranjbar-Bourani, M., & de Neufville, R. (2015). Improving the Lifecycle Performance of Engineering Projects with Flexible Strategies: Example of On-Shore LNG Production Design. *Systems Engineering*, 18(3), 253–268.

Cho Chung-Suk, & Gibson G. Edward. (2001). Building Project Scope Definition Using Project Definition Rating Index. *Journal of Architectural Engineering*, 7(4), 115–125.

Dumont Peter R., Gibson G. Edward, & Fish John R. (1997). Scope Management Using Project Definition Rating Index. *Journal of Management in Engineering*, 13(5), 54–60.

Figueiredo, J. M. de, & Kyle, M. K. (2006). Surviving the gales of creative destruction: the determinants of product turnover. *Strategic Management Journal*, 27(3), 241–264.

Gaimon, C., & Singhal, V. (1992). Flexibility and the choice of manufacturing facilities under short product life cycles. *European Journal of Operational Research*, 60(2), 211–223.

Galle, W., De Temmerman, N., & De Meyer, R. (2017). Integrating Scenarios into Life Cycle Assessment: Understanding the Value and Financial Feasibility of a Demountable Building. *Buildings*, 7(4), 64.

Gibson, J. G. E., Irons Kyle T., & Ray Michael P. (2000). Front End Planning for Buildings. *Building Integration Solutions*. Proceedings.

Gupta, A., & Maranas, C. D. (2003). Managing demand uncertainty in supply chain planning. *Computers & Chemical Engineering*, 27(8–9), 1219–1227.

Johnson A. (1996). Rehabilitation and re-use of existing buildings. *Building maintenance and preservation: a guide to design and management.* Oxford: Architectural Press, 209–230.

Langston, C., Wong, F. K. W., Hui, E. C. M., & Shen, L.-Y. (2008). Strategic assessment of building adaptive reuse opportunities in Hong Kong. *Building and Environment*, 43(10), 1709–1718.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering*, 6(4), 239–242.

Mallach, A. (2006). Bringing buildings back: from abandoned properties to community assets: a guidebook for policymakers and practitioners. *New Brunswick: National Housing Institute.*

Maslak Katie, Franz Bryan, Molenaar Keith, & Kremer Gül. (Unpublished). Strategic Development of Flexible Manufacturing Facilities. Submitted to: *Engineering, Construction and Architectural Management Journal.*

Maslak Katie, Franz Bryan, Molenaar Keith, & Kremer Gül. (2018). State-of-the-Practice in the Design and Construction of Flexible Facilities. *Construction Research Congress 2018*.

McConnell, S. (2006). *Software Estimation: Demystifying the Black Art.* Microsoft Press.

Oppenheim, A. N. (1992). *Questionnaire design, interviewing and attitude measurement.* Continuum, London.

Pagell, M., Newman, W. R., Hanna, M. D., & Krause, D. R. (2000). Uncertainty, flexibility, and buffers: Three case studies. *Production and Inventory Management Journal*; Alexandria, 41(1), 35–43.

Pillkahn, U. (2008). *Using Trends and Scenarios as Tools for Strategy Development: Shaping the Future of Your Enterprise*. John Wiley & Sons.

Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2008). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. *Systems Engineering*, 11(3), 246–262.

Sahinidis, N. V., & Grossmann, I. E. (1991). Multiperiod investment model for processing networks with dedicated and flexible plants. *Industrial & Engineering Chemistry Research*, 30(6), 1165-1171.

Sakhari, V., Chinowsky, P., Taylor, J. (2017). Grand Challenges in Engineering Project Organization. *The Engineering Project Organization Journal*. 7(1).

Schnaars, S. P. (1987). How to develop and use scenarios. *Long Range Planning*, *20*(1), 105–114.

Seeley, I. H. (1972). *Building economics: appraisal and control of building design cost and efficiency.* Macmillian.

Slater, S. F. (1993). Competing in high-velocity markets. *Industrial Marketing Management*, *22*(4), 255–263.

Stake, R. E. (1995). *The Art of Case Study Research*. SAGE.

Taylor John E., Dossick Carrie Sturts, & Garvin Michael. (2011). Meeting the Burden of Proof with Case-Study Research. *Journal of Construction Engineering and Management*, 137(4), 303–311.

Tih-Ju, C., An-Pi, C., Chao-Lung, H., & Jyh-Dong, L. (2014). Intelligent Green Buildings Project Scope Definition Using Project Definition Rating Index (PDRI). *Procedia Economics and Finance*, 18, 17–24.

Thomas, D., Burns, J., Audette, J., Carroll A., Dow-Hygelund, C., Hay, M. (n.d). Clinical development success rates 2006-2015. <BIO.org> (Aug. 1, 2017).

Tsiakis, P., Shah, N., & Pantelides, C. C. (2001). Design of Multi-echelon Supply Chain Networks under Demand Uncertainty. *Industrial & Engineering Chemistry Research*, 40(16), 3585–3604.

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega*, 3(6), 639–656.

Yin, R. K. (2017). *Case Study Research and Applications: Design and Methods*. SAGE Publications.

Zhang, G., Liu, R., Gong, L., & Huang, Q. (2006). An Analytical Comparison on Cost and Performance among DMS, AMS, FMS and RMS. *Reconfigurable Manufacturing Systems and Transformable Factories*. 659–673.