

Assessing the Influence of Manufacturing Flexibility on Facility Construction Costs

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Abstract

Uncertainty in product development and market demand can affect facility design and construction. Adding flexibility in manufacturing processes can mitigate this uncertainty, but can also create costly solutions. This is particularly true when manufacturing facilities have long design and construction lead times. In these cases, manufacturers take risks by starting facility construction before the product development is complete to meet time-to-market needs. Similarly, uncertain market demand can create the need to build facilities with additional volume or the ability to expand. This paper presents an analysis of how manufacturing flexibility affects building system costs and proposes a solution for understanding the tradeoffs. The research method maps various types of manufacturing flexibility (e.g., process, routing, volume, etc.) to ASTM UNIFORMAT II building systems (e.g., substructures, shell, interiors, etc.). Based upon this mapping, initial cost models are proposed to explore the relationship between manufacturing flexibility and facility construction cost. The models are intended for use in the earliest stages of capital facility planning. These results will help manufacturing facility owners, designers, and constructors make informed decisions about how to build flexibility into their buildings at lower costs while mitigating for uncertainty and meeting time-to-market needs.

Keywords

Flexible Facilities, Manufacturing and Life Sciences, Cost Estimation, Uncertainty

1. Introduction

The manufacturing and life sciences (MLS) industry is fast-moving, dynamic, and ultra-competitive. When combined with uncertainties in product, process, and market demand, the development and construction of manufacturing facilities remains a challenging, yet critical, component to the overall success of an organization. If properly developed, these facilities can provide a competitive advantage for the organization. The primary goal in manufacturing facility design is to ensure the building can support the needs of the manufacturing processes housed within. For this reason, traditional facility development approaches have focused on designing a facility around a specific manufacturing platform. These custom-designed, high-cost facilities have proven to be very effective for supporting their specific design intent. However, over time, manufacturing processes are required to adapt to new products, technologies, or demands, which can create unforeseen impacts on the ability of a facility to function as

intended. Optimized facilities (i.e., dedicated facilities) are often unable to absorb these changes to the manufacturing system, creating a situation in which a manufacturing organization must make the costly decision to either modify the existing building or construct a new facility.

The incorporation of flexibility in the design of manufacturing facilities is one method of enabling a facility to support both current and future production needs, which can ultimately increase the usable life of a manufacturing facility [1, 2]. Flexibility can be incorporated into a facility through a wide array of design choices. The designer is often tasked with sifting through potential design options and providing an up-front cost for such facilities early in the design process. This requires consideration of future process changes that may take place, sometimes before the final manufacturing process is fully defined. However, by gaining a comprehensive understanding of the cost influence manufacturing systems have on the physical building, specific strategies can be developed to increase the flexibility of a facility [3].

2. Research Motivation

Flexibility in the manufacturing industry is not a new concept. By incorporating flexibility within manufacturing processes, production systems can withstand a greater variety of disruptions and uncertainty [4]. Typically, flexibility is addressed at the process level, through flexible, adjustable, or reconfigurable manufacturing systems [5, 6]. However, concentrated efforts in understanding how manufacturing flexibility affects the physical manufacturing facility have not been undertaken. Flexibility, in terms of the facility, can provide a multi-faceted benefit to individual organizations. Not only does facility flexibility have the potential to accelerate design and lower development costs, it can also provide the ability to support multiple manufacturing products and processes while simultaneously responding to short- and long-term uncertainties associated with each. These uncertainties may include process, product, market demand, and regulatory approvals.

This research effort aims to conduct an investigation into the development of flexible manufacturing facilities through addressing a central research question: How does flexibility in manufacturing systems influence physical manufacturing facilities?

This paper describes an initial effort in developing a baseline understanding of this relationship, as well as a model for quantifying the cost impacts of facility flexibility on a physical manufacturing facility. These findings will serve as a catalyst for subsequent research efforts investigating financial cost implications of incorporating facility flexibility strategies, as well as potential flexible facility optimization methods and recommendations. The paper presents a conceptual cost model for exploring the influence of manufacturing flexibility on facility cost.

3. Model for Flexible Cost Influence

The conceptual cost model proposed in this paper combines well-established industrial engineering principles with current cost engineering industry practice. From industrial engineering research, which has become textbook knowledge, an understanding of flexibility in manufacturing systems is developed. From this understanding, an approach to quantifying the impact of flexibility on facility cost is proposed. Although many cost breakdown structures for conceptual estimating exist, the most well-established is the ASTM UNIFORMAT II approach. These two concepts are brought together to develop a conceptual cost model that relates the influences of manufacturing flexibility to physical facility systems and overall cost.

3.1 Dimensions of Flexible Manufacturing

Continuous advancements in manufacturing systems technology have rendered processes more capable, efficient, and flexible to meet the changing demands of the manufacturing industry. Processes are no longer restricted to the production of a single product and can continually adapt an array of products and demands. This ability to adapt has been achieved through the incorporation of eight seminal dimensions of manufacturing flexibility, seen in Table 1. These eight dimensions of flexibility represent the base manufacturing concepts used for comparison against facility building elements in the following cost optimization model [5, 7].

Each of these FMS dimensions can occur individually or in unison to enhance the capabilities of a manufacturing system. Although flexible manufacturing systems have the inherent potential for flexibility, some physical change to the system is generally required for that flexibility to fully materialize. Furthermore, the scale of change to a facility can vary significantly depending on the specific manufacturing application. Some of these changes, including machine, process, and product are generally contained within the equipment alone and have minimal impact on a physical facility. However, expansion, volume, and routing flexibility have significant potential to influence building

design and layout [3]. For example, if a process is expanded to meet increased production demands (i.e., expansion flexibility), additional pieces of machinery may be added to a production line resulting in additional building footprint and service requirements. Because of the wide array of potential manufacturing changes and resulting impact on a facility, a varying level of investment must be made to develop a facility that has the ability to adapt to changes in both manufacturing process and facility.

Table 1. Dimensions of Manufacturing Flexibility

Dimension of Flexibility	Description
<i>Machine</i>	The ability to make changes to the machine system with minimal production interference
<i>Process</i>	The ability to vary the steps required to complete the task, allowing several tasks to be completed by the system
<i>Product</i>	The ability to produce multiple products on the same system with minimal alterations to that system
<i>Routing</i>	The ability to handle breakdowns and re-sequence events to continue producing the product
<i>Volume</i>	The ability to produce a significant variety in volume of the same product with minimal impact on cost
<i>Expansion</i>	The ability of the system to expand easily and (often) modularly
<i>Operations</i>	The ability to interchange the ordering of several operations for the same product
<i>Production</i>	The ability to quickly and economically vary the part variety for any product that the system can produce.

3.2 UNIFORMAT II Standard

The ASTM UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis, was developed by the National Institute of Standards and Technology (NIST) [8]. It provides a generalized approach to cost estimating classification and categorization of physical building systems. This classification system is widely accepted by the design and construction industry as a standardized system for general building elements and site work. This system was selected for use in categorizing the physical components of a manufacturing facility as it represents an established and well-respected means of organizing building components in both broad and individual terms. Within the UNIFORMAT II categorization system, building elements are classified using three distinct levels of hierarchical categorization: Level 1, 2, and 3. These three levels provide a means to organize building elements from broad groupings down to singular building systems [8].

Level 1 classification includes seven major groupings of physical building elements, such as substructure, shell and services, while Level 2 elements consist of seventeen subgroups within the respective major groupings. Level 3 categories break down subgroup elements to the lowest individual level, providing context for the identification of specific building elements. In this initial cost estimation approach, we used the UNIFORMAT Level 1 categories. Table 2 is a high-level listing of UNIFORMAT II categories for example [8].

Table 2. UNIFORMAT II Building Systems

Level 1	Level 2	Level 3 (list not inclusive)
Substructure	Foundations, basement construction	Standard foundations, slab on grade, basement excavation
Shell	Superstructure, exterior enclosure, roofing	Floor construction, exterior walls, roof coverings
Interiors	Interior construction, stairs, interior finishes	Partitions, wall finishes, fittings
Services	Conveying, plumbing, HVAC, fire protection, electrical	Elevators & lifts, cooling generating systems, fire protection specialties, electrical service & distribution
Equipment & Furnishings	Equipment, furnishings	Institutional equipment, other equipment, fixed furnishings
Special Construction and Demolition	Special construction, selective building demolition	Integrated construction, special controls & instrumentation, building elements demolition
Building Sitework	Site preparation, site improvements, site mechanical utilities, site electrical utilities	Site earthwork, roadways, water supply, electrical distribution

3.3 Flexible Facility Cost Estimating Model

Traditionally in manufacturing facility design, flexibility is perceived to be a costly strategy to implement [4]. In the earliest stages of decisions, the cost of including flexibility into the facility must be compared against the facility's increased capabilities. As such, the first step of considering flexibility is to determine the premium for adding flexibility and then compare it to the flexibility that can be achieved by the internal manufacturing system. The model proposed in this paper will address this first step and provide a high-level cost analysis for adding manufacturing flexibility beyond the typical dedicated use design. It will provide early support for decisions critical to designing facilities that are capable of meeting future flexibility needs. Because this model will be implemented in the initial stages of design, its purpose is only to provide an approximation of first cost. It will not address lifecycle cost of the facility or the potential additional benefits from future manufacturing flexibility.

The flexible facility cost model is grounded in the initial facility cost estimate for a dedicated facility (termed *DedicatedCost* in later equations). In the dedicated facility, the facility design is optimized for the known product and processes. This cost estimate must assume no manufacturing flexibility, which is typical for dedicated designs. The dedicated facility estimate serves as a baseline for which owners and designers can compare potential flexible facilities costs.

Users must then determine if each dimension of manufacturing flexibility (from Table 1) will be beneficial in the short- or long-term. In this model, each dimension of flexibility is considered to be independent, and thus must be addressed as such. If the user determines that the manufacturing process should retain such flexibility, then the desired extent of that flexibility must be determined on a scale from no change to the maximum desired flexibility. In testing, it was determined that users could benefit from defining two flexibility scenarios: moderate flexibility and extreme flexibility. This allows the team to analyze the extent of flexibility desired and model some uncertainty. Additional scenarios beyond moderate and extreme did not add significantly more information to the conceptual estimate.

Once the extent of the desired manufacturing flexibility is determined, the impact to each building system should be considered. Figure 1 depicts the user-defined relationship between each manufacturing flexibility dimension and each potential building system within UNIFORMAT II. By understanding these relationships, specific components of a facility can be identified and strategically designed to increase the facility flexibility with respect to multiple manufacturing process flexibilities, as well as limit the restricting impact on respective manufacturing systems.

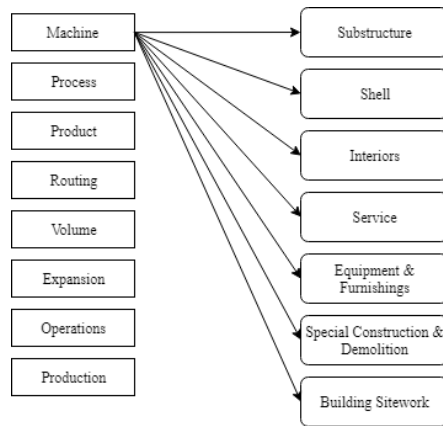


Figure 1. Flexible Manufacturing Dimension Facility Design Implication

The impact on the building systems for a ‘moderate’ amount of a specific type of process flexibility may be different than the impact for ‘extreme’ flexibility. For example, a desire for moderate expansion flexibility may affect only the substructure and interiors whereas an extreme amount of expansion flexibility may affect all seven building systems. Furthermore, each of these building systems may not be affected equally. For this reason, an influence scale was developed, ranging from ‘no impact’ to ‘very strong,’ to improve the accuracy of the estimate. Table 3 provides the influence scale of the relationship between each dimension of manufacturing flexibility and the respective physical building elements. By mapping the type and level of each type of desired process flexibility against the influence on the building, users can then calculate the cost premium across all of the building systems for adding any combination of process flexibilities (termed *FlexibilityPremium* in later equations).

Table 3. Relationship Cost Influence Scale

Influence	Cost Impact (Deterministic)
No Impact	0%
Weak	1-5%
Moderate	5-15%
Strong	15-30%
Very strong	< 30%

The flexible facility cost model finds the total *FlexibilityPremium* (Equation 2) for a facility that includes desirable dimensions of manufacturing flexibility. Equation 1 represents how each UNIFORMAT II building system is included in the equations that follow. Equation 1 represents the cost implication for a single UNIFORMAT II building system (j) defined as D_j , based on the total desired flexibility. To account for moderate or extreme scenarios, the maximum value is taken in Equation 1. The cost impact (see Table 2) is defined as $C_{i,j}$ where i represents the flexible manufacture dimensions (D 1 to 8), and j represents the UNIFORMAT II classification (1 to 7). \vec{C}_j represents the vector of the cost implications from all flexible dimensions within a specific UNIFORMAT II building system (j). \vec{R}_i Represents a vector of relations of all flexible dimensions with a specific Dimension (i). Finally, to account for relationships (R) between flexibility dimensions (D), the user defines an 8 by 8 matrix as R where the sub-index represents the flexible manufacturing dimensions, where the value of R_j varies from 0 to 1.

$$D_j = \max_{i=1..8} [C_{i,j} + \vec{C}_j * \vec{R}_i] \quad (1)$$

$$FlexibilityPremium = \sum_{j=1}^7 \left[D_j * \frac{CostImpact_j}{DedicatedCost} \right] \quad (2)$$

The *FlexibilityPremium* is a factor that approximates the additional cost an owner would pay if they decide to move from a dedicated facility to a facility that can accommodate their desired manufacturing flexibility. The owner and designer will need to trade off these additional costs with the benefits of manufacturing flexibility, which frequently include getting products to market sooner, minimizing costs to meet additional demand, and/or minimizing costs for manufacturing platform modifications or changes.

4. Preliminary Testing

To test the proposed understanding, the above concepts, relationships, and formulas were amalgamated into a flexible facility cost estimating model. This model was examined by a group of industry professionals to provide input on their perceived level of influence between manufacturing flexibility and the building system. Participants were representatives of various manufacturing companies across the manufacturing and life sciences industry, along with design and construction professions who specialize in manufacturing facilities. All participants had familiarity with the design, construction, and maintenance of facilities and had a general understanding of manufacturing processes and operations industrywide.

The research team has been able to develop some initial findings about the cost impact of flexibility on physical building systems from its analysis of existing facilities and discussions with the industry professionals. In one building scenario, the team found that the manufacturing flexibility dimensions of expansion, operations, and production flexibility had the greatest impact on building systems. The remaining five flexibility dimensions can also affect facility building systems, but their impacts are highly dependent on the manufacturing process in question. In this building scenario, this team also determined that the UNIFORMAT II building systems of substructure, shell, and services were most highly affected by the inclusion of manufacturing flexibility. Interiors were also affected, but to a lesser extent. Thus, the primary cost impacts on a facility come from including flexibility into these systems. In these discussions, it was determined that the relationships between flexibility dimensions were important, but difficult to estimate. This was partly because the relationships were heavily dependent on process type and industry. More work will need to be done to determine if these relationships are generalizable or need to be estimated on each project.

5. Limitations and Conclusions

This paper develops the relationships between manufacturing process flexibility and facility building systems. It then proposes a model so that users can determine a cost “premium” for including flexibility at the facility level. Perhaps the largest limitation to the current cost model, besides its consideration of manufacturing flexibility independence, is its inability to deal with the inherent uncertainty of estimates at a conceptual stage of design. This limitation can be addressed through a use of Monte Carlo simulation. Costs for each building system can be estimated in a range and the cost impacts (Table 3) can also be estimated in a range. These ranges can be used as inputs for a Monte Carlo simulation to produce a flexible facility premium cost range as opposed to a single point estimate. This range will better represent the potential final cost for the project. Additionally, and perhaps more importantly, the simulation will produce a sensitivity analysis that can show which dimensions of flexibility have the most impact on which physical building systems. Understanding these relationships may also aid in the understanding of the relationship between impacts. In the next phase of research, the team will validate the process and calibrate the results for a variety of manufacturing facilities across the industry. With more case applications, a better understanding of the relationship between flexibility manufacturing and capital facilities cost will emerge.

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