The Impact of Material Handling on Manufacturing Process Plan Selection

by
Ian Edward Sargent

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Industrial Engineering
(Honors Associate)

Presented November 26, 2018
Commencement June 2019

AN ABSTRACT OF THE THESIS OF

Ian Edward Sargent for the degree of Honors Baccalaureate of Science in Industrial Engineering presented on November 26, 2018. Title: The Impact of Material Handling on Manufacturing Process Plan Selection.

Abstract approved:____

David S. Kim

The total manufacturing cost for a part is determined by its process plan, and the total cost includes both processing and material handling costs. This research examines the cost impact of assuming an arbitrary layout when evaluating alternative process plans for production in a new facility. A designed experiment was developed to explore the impact of this assumption. The experiment includes seven different factors that define a manufacturing scenario. The factors are: material cost, material removal rate, part volume, possible blank types, load/unload time, joining rate, and labor rate. The objective of this research is to determine which of these factors have a large impact on whether the assumption of an arbitrary layout is likely to lead to error in selecting the lowest cost process plan, and to use the results to identify specific manufacturing scenarios where the arbitrary layout assumption is not appropriate. Four factors were determined to be important: part volume, load unload time, material cost, and labor rate. The relative importance of these factors was then evaluated, and some manufacturing scenarios are identified where layout optimization and process plan optimization should be integrated.

Key Words: Material Handling, Facility Layout, Process Plan, Experimental Design

Corresponding e-mail address: sarge5895@gmail.com

The Impact of Material Handling on Manufacturing Process Plan Selection

by
Ian Edward Sargent

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Industrial Engineering
(Honors Associate)

Presented November 26, 2018
Commencement June 2019

Honors Baccalaureate of Science in Industrial Engineering project of Ian Edward Sargent presented on November 26, 2018.

APPROVED:

David S. Kim, Mentor, representing School of Mechanical, Industrial, and Manufacturing Engineering

Karl Haapala, Committee Member, representing School of Mechanical, Industrial, and Manufacturing Engineering

Matt Campbell, Committee Member, representing School of Mechanical, Industrial, and Manufacturing Engineering

Hector Vergara, Committee Member, representing School of Mechanical, Industrial, and Manufacturing Engineering

Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Ian Edward Sargent, Author

ACKNOWLEDGEMENTS

Both the Boeing Company and the Oregon Metals Initiative provided essential funding for the research in this thesis. I would like to extend my thanks for their assistance. Specifically, Rob Tsunehiro, Matthew Carter, Eric Eide, and Bill Gerry of the Boeing Company all provided useful input for the topic discussed in this thesis.

I would like to thank my committee members: Hector Vergara, Matt Campbell, and Karl Haapala for their time and effort in serving on my thesis committee. I would also like to thank my fellow research lab members: Rothanak Chan, Brandon Massoni, and Alan Grier whose work made this thesis possible. I would also like to thank my mom, sister and stepfather for their love and support. Finally, I would like to thank my mentor David S. Kim; without his extraordinary effort, time, and guidance, this thesis would not be possible.

TABLE OF CONTENTS

TABLE OF APPENDICES

1. Introduction

1.1. Problem Definition

A common manufacturing process for producing metals parts is to mill the parts from a solid piece of metal. This solid piece of metal may take on different forms such as a rectangular block, forging, or circular bar stock and will be referred to as a “blank.” One negative aspect of this process is that there is typically a significant amount of blank material that does not end up in the part and must be recycled or scrapped. The emergence of new manufacturing joining processes, such as linear and rotary friction welding, and different types of additive manufacturing processes (e.g. 3D printing processes) allows the creation of new “blanks” for milling. These new “blanks” are assembled from parts such as smaller rectangular blocks, circular bar stock, and metal plates. This process allows a new method to be used to produce the final part.

Thus, the new manufacturing technologies make available new alternative manufacturing process plans for a part (a process plan can be defined as the detailed list of the steps and processes required to manufacture a particular part in a certain way). Should the part be milled from a single blank, or should a new part be constructed from smaller blanks before milling? The use of more blanks results in lower raw material costs and less material waste. There is a tradeoff, however. Costs are incurred for utilizing additional manufacturing processes (e.g. joining) and additional *material movement*. If manufacturing process plans are being developed for production in a *new* facility, the material movement cost that is part of the plan is not known. The impact of these unknown material movement costs is the focus of this thesis.

The unknown nature of these costs occurs because an optimal plant layout depends on the manufacturing process plans and production volumes for all parts produced in the plant. The part's manufacturing process plan will determine its routing for material handling purposes within the facility, which will in turn affect the part's material handling costs. This idea can be illustrated with the use of an example. One manufacturing process may call for a part to be machined out of one rectangular bar stock blank. This would mean that the part does not have to go through any additive or friction welding processes and its routing would call for it to be moved from storage to machining and then through testing before being sent to a finished product area. Another process plan may call for this part to be manufactured from a linear friction weld of two rectangular bar stock blanks. This plan would mean that blanks would have to be moved from the material storage department to a linear friction welding department, then the welded blanks would be moved to a quality testing department. After these moves the part would be moved to machining, and then a final testing department before going to the finished product area. When multiple parts and production volumes are considered, it is clear that the optimal facility layout and thus, move distances are not known.

For the purposes of this research, it is assumed that decision-makers will select the optimal configuration when deciding between different manufacturing process plans, which is defined as the manufacturing process plan with the lowest estimated total cost. The unknown nature of the final facility layout for the part means that there will be uncertainty when estimating the material handling costs for that part's potential manufacturing plan since material handling costs compose a portion of the part's total cost. One way to deal with this issue is to assume an arbitrary, non-optimized layout for the purposes of estimating material handling costs. An arbitrary layout is defined in this research as a layout that is used during process plan generation to obtain material handling cost estimates, but is not optimized for any specific process plan. If the material handling costs are large enough, the part's total cost could vary significantly when calculated for different layouts. This raises the question: Is this variability large enough to affect which manufacturing process plan is ultimately selected?

In this thesis, it is hypothesized that the impact of material handling costs on the selection of minimum cost manufacturing process plans depends on the particular manufacturing scenario being considered. For example, the manufacturing of low-cost wood products would be characterized by relatively low material costs. This scenario may result in material handling costs having a significant impact on any process plan decision. The research objective is to identify scenarios where a more in-depth analysis of the facility's potential layout is required to make correct manufacturing process plan decisions.

2. Literature Review

The literature review for this project will cover two separate topics. The first part of this section will discuss research in the field of computer-aided process plan optimization. The second half of this section will discuss literature in the field of facility layout optimization. Process plans are determined by part design, which is defined as the way in which the part is chosen to be manufactured. The choices made during part design encompass all the steps from the selection of raw material types to if joining and/or additive processes will be used in its creation. It is important to note that the part design does not include the final geometry and size of the part. These aspects are treated as a fixed input for the purposes of this project. The papers referenced in the field of computer-aided process plan generation will discuss methods to optimize the manufacturing of parts so that they are produced in a cost-efficient manner. More specifically, the literature will focus on situations where manufacturing can be potentially improved by utilizing joining processes. This research examines process planning in situations where joining is an available process, so it is necessary to review literature that discusses similar situations.

The facility layout optimization literature review will focus on the subset of research that details how flow data is incorporated into the layout problem. The flow data for a particular problem is determined by the process plans for the parts to be produced in that particular facility. Most research in this field treats the flow data as a fixed input used in solving the layout problem. In these situations, the process plan problem and layout problem are treated as independent issues. The goal of this section is to show that research is not available for situations where the flow data is unknown, and when the process plan problem and the facility layout problem must be solved interdependently.

2.1. Computer-Aided Process Plan Optimization Literature

Massoni and Campbell (2017a) detail their research in developing process plans for three dimensional complex parts. Their method decomposes these parts into blanks so that joining processes can be used to create the final assembly in a cost-efficient manner (Massoni & Campbell, 2017a). Utilizing these joining processes, significant savings can be made for complex parts that would otherwise be machined out of a single blank (Massoni & Campbell, 2017a). Joining several smaller parts together can reduce the total cost of the part if the machining and material savings outweigh the additional process costs (Massoni & Campbell, 2017a). The method proposed by this research, utilizes linear and rotary friction welding processes to calculate several different ways for assembling a part from these smaller blanks (Massoni & Campbell, 2017a). Costs are then computed for each of these configurations so that they can be compared (Massoni & Campbell, 2017a). Massoni and Campbell's research serves as the foundation for the Katana tool that will be used in this research (2017a). Most of the cost models discussed in this paper come from this research

Hoefer, Chen, and Frank (2017) created ANA, a software that provides feedback about manufacturability for different part designs. Their research objective is to ensure that effective decisions are made early in the design process, as errors in the conceptual design stage can affect the final cost of the part significantly (Hoefer et al., 2017). ANA utilizes geometric algorithms to create manufacturability metrics for machining, die-casting, and welding processes (Hoefer et al., 2017). Colored 3D graphical models combine with these metrics to provide user feedback, so that they can make design improvements and select effective manufacturing processes (Hoefer et al., 2017). This research does not include costing models and provides feedback that is not cost-based. It also lacks functionality for advanced joining processes, such as linear friction welding and rotary friction welding.

Fu, Eftekharian, and Campbell (2013) conducted research on developing manufacturing plans for machinable parts based on the associated CAD files. A plan is developed for the part that details all of the machining processes required to machine the part to its desired shape and dimensions (Fu et al., 2013). The research also accounts for geometries that are not machinable (Fu et al., 2013). Fu, Eftekharian, and Campbell's research (2013) does not include advanced joining processes, and is solely focused on machining. The optimization of process plans is also not the primary focus of their research.

Chan, Haapala, and Campbell (2018) discuss research for using voxels to assess the machinability of a given part or geometry. The method is able to visually highlight the sections of a part that will be non-machinable, and thus allow designers to fix these errors (Chan et al., 2018). Contemporary part designers sometimes fail to account for machinability when designing parts, so it is important to be able to detect which regions may cause trouble (Chan et al., 2018). As mentioned above, this research focuses on process plans that can incorporate joining techniques, such as friction welding. These joining techniques can sometimes be used to access areas that would otherwise be unmachinable on a part, such as the areas that Chan, Haapala, and Campbell's (2018) research would highlight as non-machinable.

2.2. Facility Layout Optimization Literature

In *Facilities Design*, Heragu (2016) mentions the importance of material handling, which helps justify the impetus for this paper. Twenty to forty percent of a product's cost can be attributed to costs that come from the material handling process (Heragu, 2016). This data shows that for some manufacturing scenarios, an inefficient layout could drastically increase the cost required to produce a product. One of the data requirements for making layout decisions is the frequency of trips between departments (Heragu, 2016). Heragu (2016) mentions that if quantitative data is not available, then qualitative frequency relationships can be used as well. However, in order to create some sort of quantitative or qualitative relationship between departments, something about the part's production process, and thus design, must be known. There is a lack of current research where the layout and part design/process plan decisions are treated interdependently.

Rosenblatt (1986) mentions that effective facility layouts can reduce costs by 10-30%, implying that the layout can have a significant cost impact on the process plans selected for different part designs. Rosenblatt (1986) addresses a dynamic facility layout problem, where the layout is optimized to allow for rearrangement during different time periods. Deterministic flow data is an input for the model, which is used to create a From-To flow matrix for each of the time periods (Rosenblatt, 1986). Because of this, the method proposed by Rosenblatt (1986) requires that information is known about a part’s flow data, which means that part’s process plan must have been finalized.

Palekar et al. (1992) develop an exact method and heuristics to solve a dynamic layout problem where interdepartmental material flows are uncertain. To account for this difficulty, a probability is associated with the various potential flow matrices from each period (Palekar et al., 1992). Then, the expected cost of material handling can be minimized for each period by using the probabilities associated with each flow matrix (Palekar et al., 1992). This differs from the problem proposed in this research for two reasons. First, because the problem is approached as a dynamic layout problem, the developed methods solve for the sum of both the rearrangement costs and the expected material handling cost. In this research, rearrangement costs are not considered because the goal is not to optimize the layout over several different time periods. Secondly, in this research, interdepartmental flows are unknown as the part design is not known.

Kulturel-Konak et al. (2004) study the unequal area facility layout problem considering both routing flexibility and production uncertainty. The paper attempts to solve the problem while accounting for robustness to uncertainty and flexibility for future changes (Kulturel-Konak et al., 2004). A robust solution is one that is effective across a variety of different production scenarios, while a flexible solution is one that can easily adapted to new circumstances (Kulturel-Konak et al., 2004). To account for production uncertainty, the interdepartmental flows are modeled probabilistically (Kulturel-Konak et al., 2004). In contrast, in the research conducted under this thesis work, part routings and, thus, interdepartmental flows become fixed once the various process plans for all parts have been determined. This means that neither robustness nor flexibility is considered in the layout optimization. Yang and Kuo (2003) develop an analytic hierarchy process (AHP) and data envelopment analysis (DEA) approach to solve a facility layout problem. The researchers assume that flow and routing data can be collected to use in evaluating layout alternatives (Yang & Kuo, 2003). In contrast, in the research conducted under this thesis work, a part's flow data and routing data are unknown, because the part design is not fixed. Because of this, such an assumption would not be valid for the research in this thesis.

Storage location optimization is another possible research area that connects to this thesis. For this area, pick lists would analogize to process plans and warehouse storage locations to department locations. If more research is desired on contemporary facility layout optimization literature, this area could also be considered for review.

3. Research Overview

Under what circumstances do facility layout and process plan decisions have to be integrated in order to minimize production costs? The approach utilized to answer this question will be experimental. A set of factors that define different production scenarios will be identified, and a factorial experiment will be conducted to ensure that the factor space is comprehensively examined. More specifically, the experiment will be a screening experiment utilizing a fractional 2^{7-2} experimental design. For each factor, a low-end and high-end value will be specified.

Seven different factors were identified to model different manufacturing scenarios for this research. These factors were identified from the cost models present in the process plan generation software used to conduct this thesis. A list of the factors is below:

- Material Cost
- Material Removal Rate
- Part Volume

- Possible Blank Types
- Load/Unload Time
- Joining Rate
- Labor Rate

To compute costs for different treatment combinations, a software tool, called Katana, will be used to identify the lowest cost process plans. These process plans will be identified with no consideration of material handling costs required to produce the part.

The experiment will be performed twice using different part geometries as inputs for Katana. Different geometries can differ in regard to the feasibility of certain joins, and the ultimate cost of manufacturing the part. Because of this, it is possible that certain factors will be important for a particular geometry, but unimportant for the other tested geometry.

Once Katana has generated the lowest cost process plans, the process plan costs will then be externally adjusted by adding the appropriate material handling costs for each plan, which are dependent on the facility layout. To simulate the impact of varying levels of material handling, low- and high-level material handling costs will be computed and used in the cost calculations.

Responses will be computed that quantify the impact of material handling costs on process plan decisions. Four responses will be used to determine whether different layouts for a manufacturing scenario may affect computations in such a way as to change a part’s optimal configuration. The four responses are (in relative order of importance): rank correlation, percentile correlation, average percent change between high-level and low-level material handling costs, and lowest cost configuration percent change between high-level and low-level material handling costs. Once the responses are calculated, an analysis will be performed to determine what factors significantly affect the layout question. Then, the relevance of certain treatment combination to real-life manufacturing scenarios will be assessed.

4. Methodology

4.1. Organization of the Methodology Section

This research utilizes Katana to develop process plans, so an overview will be given of how these plans are created within the software. Next, as this research is focused on the topic of material handling, details of how the material handling costs are computed will be given. Specifically, this research uses high and low-level material handling costs to compare the effect of an arbitrary layout on various treatment combination. After explaining material handling costs in general, more specific details on how the low and high-level material handling costs are computed will be given. Next, since the approach used in this research is experimental, an overview of the experimental design will be presented. The factors that are being tested within the experiment will then be described in detail. As this is a two-level experiment, justification will also be given for how the high and low-end values were determined for each factor. In order to account for variance in part geometries, the experiment will be performed with two separate part geometries. An explanation will be given of why this is necessary, and why the geometries used in this research were selected. Finally, an explanation of the numerical responses used in the experimental design, and how they will be evaluated, is given.

There are three additional topics that are discussed in Appendix A: how cutting planes are found within Katana, the process that was used to eliminate identical process plans during the research, and the theoretical and practical limits on cross-sectional joining area.

4.2. Estimating Process Plan Costs

A process plan defines all of the steps necessary to manufacture a particular part. These steps can be divided into four categories: material handling, joining, material removal, and auxiliary processes. In the context of this research, each of these categories is defined below:

- *Material handling*: All of the processes required to move a physical piece of material from one location to another
- *Joining*: The process used to join two separate parts together. In the context of metal parts, this is could be some type of welding. For wood parts, this process could be gluing.
- *Material Removal*: The process used to alter a part by material removal into its final shape. For example, milling would be one such process.
- *Auxiliary Processes*: The processes that follow joining and material removal processes to ensure quality and durability. For example, quality checks and non-destructive testing would fall under this category. For simplification purposes all such processes will be combined into one process termed “Auxiliary”.

As mentioned above, a software tool named Katana will be used to identify low cost process plans <u>with no material handling costs included</u>. In Katana, these process plans are created using a geometric search algorithm to identify potential cutting planes that are potential joining locations. This process is called area decomposition (Massoni & Campbell, 2017b); more information on this topic can be found in Appendix A.1. There are many possible ways a part can be decomposed with cutting planes, so Katana uses a heuristic optimization search procedure to generate and identify low-cost process plans based on these cutting planes. These process plans include all necessary joining, material removal, and auxiliary steps required to produce the part. For each of these steps, Katana calculates a cost based on parameter values associated with that step (Katana contains cost models that it uses to computes costs for each of the four different types of process steps). All of the factors are connected to the parameters within Katana. For example, the joining rate affects the speed with which the joining process is completed. A larger part will take a longer time to complete its joining process when compared to an identical, but smaller part. Because of this increased process time, this step will be more expensive for the larger part.

When producing process plans, Katana can occasionally create one or more process plans that are redundant. In order to eliminate this redundancy, these process plans are manually eliminated; more information can be found in Appendix A.2.

4.3. Material Handling Cost Computation

Material handling will be calculated using Equation 1 below.

Equation 1: Material Handling Cost per Unit Move

$$Cost\ per\ Move = \left(LoadUnload\ Time + \frac{Distance}{Speed}\right) \times (\#\ of\ Operators\ \times Labor\ Rate)$$

Each move represents a material handling move from one process or facility location to another process or facility location. As a part is broken up into more blanks, more moves will be required.

This model only accounts for loaded material handling moves. Empty material handling moves are ignored for this research. This understates the magnitude of the material handling cost. In worst case scenarios, the material handling distance could be doubled from what is accounted for in the above model. For most realistic situations, empty travel will occur to some degree. A more accurate cost model should probably account for empty travel to better model realistic scenarios.

Batch size is also not included in the formula, because a batch size of one is assumed to be used for all production processes. This is due to a limitation within Katana. In reality, it is likely that a batch size larger than one will be used. This is a limitation of the current research and should be looked at in the future. The variables used in the formula are described below.

- *Labor Rate* is a fixed input, describing how much labor costs to perform material handling tasks.
- *LoadUnload Time* is the amount of time it takes for a part to be loaded and unloaded.
- *Speed* is the average velocity with which the material handling method (e.g. a forklift) moves through the facility.
- *# of Operators* is the number of workers that it takes to operate a specific material handling method. For example, using an overhead crane commonly takes two or more operators.
- *Distance* is the rectilinear distance between two departments. When a part is moved it will travel this distance from its starting location to its ending location.

Once the cost per move is calculated, it is multiplied by the number of material handling moves present in a specific configuration's process plan to calculate the total material handling cost for that configuration. A key insight from analysis of this formula is that the material handling cost has a layout dependent component and layout independent component. The move distances are layout dependent and the load/unload times are layout independent.

4.4. Low and High-Level Material Handling Costs

Low and high-level material handling costs will be computed externally and added to process plan costs generated by Katana since the Katana-generated process plan costs will not include material handling. Because material handling costs are not considered in the process plan identification process, the process plans identified can be associated with how design engineers typically design parts to reduce costs. When parts are designed, and preliminary costs are estimated, these costs often fail to include material handling cost. Because of this, the designed part may be suboptimal, if it is designed in such a way that it incurs significant material handling costs compared to alternative designs.

Low and high-level material handling costs are obtained by adjusting the parameters shown in the material handling equation above. These costs will be given in units of cost per move and then multiplied by the number of material handling moves required to produce a specific configuration.

Below, the various inputs for Equation 1 will be described for both the low and high-level material handling costs per move. Notably, the distance input is slightly more complicated to determine than the other inputs. The distance per move is primarily based on the facility area that a process plan is created for. For example, a facility that is larger will necessarily have department centroids that are on average farther apart when compared to an identical facility with a smaller area. Because of this, the distance per move will be determined by creating an arbitrary facility layout of the proposed size with all necessary departments. These departments will then be evenly distributed throughout the facility and equally sized so that all available space in the facility is taken up. The average rectilinear distance between department centroids will then be used as the distance in calculating material handling cost per move. For this project, a material handling move will be completed in between each process, and both before and after the first and final processes, respectively.

For the low-level material handling cost per move, a facility with dimensions of 250 feet by 250 feet will be used to determine the distance to be used in material handling calculations.

For the high-level cost per move, a facility with dimensions of 1000 feet by 1000 feet will be used. The five departments that will be used in these layouts are described below. Each of these departments may be used when developing process plans for a configuration.

- *Raw Material Storage*: This department houses all of the raw material necessary to produce parts within the facility. The first step of any process plan will involve moving material from this department to either the joining or machining department.
- *Joining*: The department that performs the joining process of connecting two or more blanks to each other.
- *Material Removal*: The department that performs the material removal process, which machines the part into its final geometry. This department may also perform pre-machining operations, if necessary. A pre-machining operation performs part of the material removal process earlier in the process plan, if a certain area would become unreachable after a specific join.
- *Auxiliary*: The department that performs quality checks and other similar operations. These processes are required after each joining process or material removal process is performed.
- *Finished Part Storage*: The final department visited in any configuration's process plan. After being completed, all parts are transported to this department.

Below a detailed description the low and high-level material handling costs will be given. The computation of the low-level material handling cost will be detailed first.

4.4.1. Low- Level Material Handling Cost

As mentioned above, the low-level material handling cost will be used to simulate scenarios represented by low material handling costs per move. The values for the different variables that are part of the material handling cost equation are detailed below:

- *Labor Rate*: The labor rate for this level will use the tenth percentile hourly wage for a warehouse worker in the United States found on Salary.com multiplied by a factor of one and a half to account for the cost of external benefits to the company (2018). This value results in a labor rate of $15 per hour for the low level (Salary.com, 2018).
- *LoadUnload Time:* The load and unload time will be fixed at 0.0833 hours (or five minutes).
- *Speed*: The speed of the material handling method will be set at the lower level of cart speeds recommended by the Canadian Centre for Occupational Health and Safety ("Pushing & Pulling - Handcarts," 2018). This level is 2.73 feet per second.
- *# of Operators:* The number of operators will be set to one.
- *Distance*: This value is more difficult to attain and will be described in detail below. The value that will be used is 100 feet.

As described above, an arbitrary layout will be created to determine the average interdepartmental rectilinear distance for the chosen facility size. A facility with dimensions of 250 feet by 250 feet (or 62,500 square feet) will be created for this level. This layout is shown below in Figure 1. Using this layout, the average interdepartmental rectilinear distance was calculated to be 100 feet.

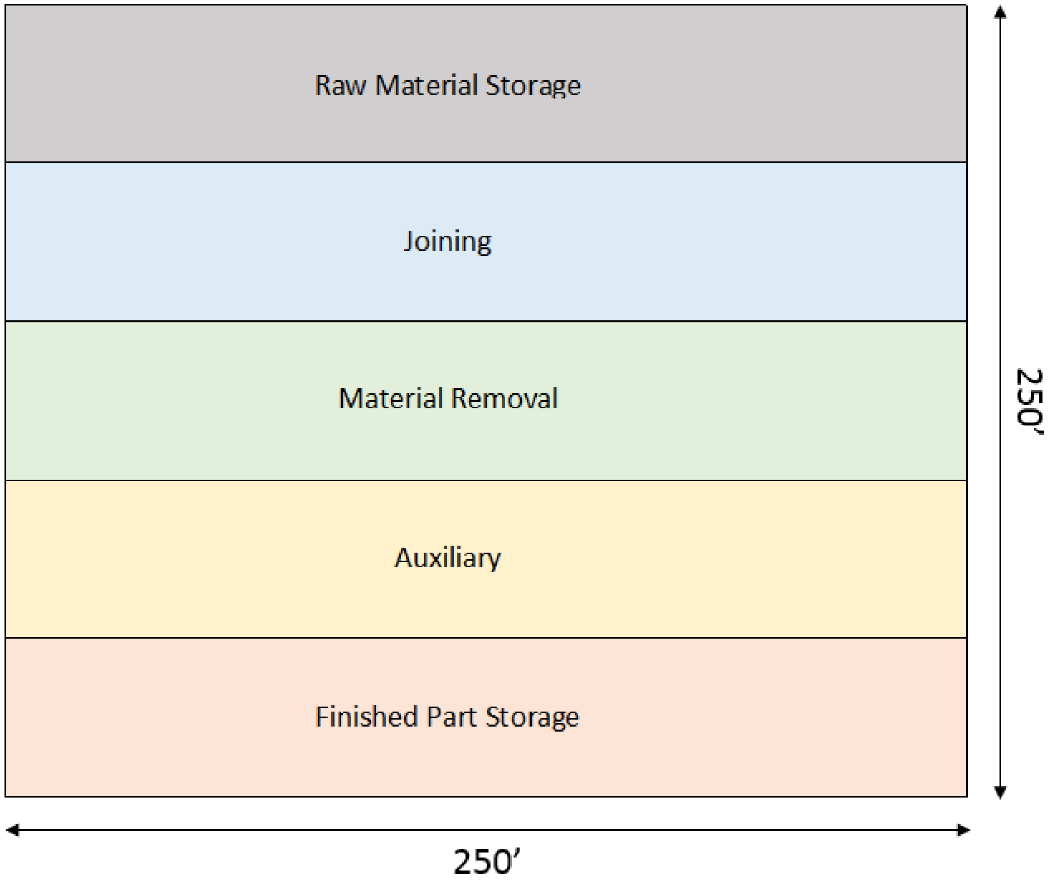


Figure 1: 250' x 250' Facility

This input was combined with the inputs described above to calculate a low-level material handling cost per unit move using Equation 1. The low-level cost per material handling move is approximately $1.40. Detailed calculations for both the layout and equation can be found in Appendix B.

4.4.2. High-Level Material Handling Cost

The same process will be repeated to find inputs for the high-level material handling cost per unit move. Once again, the values to be input will be described below:

- *Labor Rate:* The labor rate for this level will use the ninetieth percentile hourly wage for a warehouse worker in the United States found on Salary.com multiplied by a factor of one and a half to account for the cost of external benefits to the company (2018). This value results in a labor rate of $27 per hour for the high level (Salary.com, 2018).

- *LoadUnload Time:* The load and unload time will be fixed at 0.25 hours (or fifteen minutes). This value can simulate situations where the product being transported is overly large, hazardous, or fragile.
- *Speed:* To model this level the speed of an overhead crane will be used, to simulate a method typified by slow speeds. Columbus McKinnon reports speeds of 0.25 feet per second for their motorized overhead crane trolley, so this speed will be used for the experiment ("Hoist and Trolley Full Catalog," 2017). This value can simulate situations where the material being transported is either hazardous, cumbersome, or fragile.
- *# of Operators:* Notably, two operators will be used for this level as some material handling methods require two operators for safety purposes. This could be for materials that are hazardous, fragile, or cumbersome.
- *Distance:* As with above, this value is more difficult to attain and will be described further below. The value that will be used is 400 feet.

As with the low-level material handling cost, the distance to be used for this level will be found by creating an arbitrary facility with evenly distributed departments. Then the average rectilinear distance between department centroids will be used to calculate the material handling cost per unit move. For this level, a facility with dimensions of 1000 feet by 1000 feet (or 1,000,000 square feet) will be used. A layout of the created facility can be found below in Figure 2. The average interdepartmental rectilinear distance that will be used, based on the layout, is 400 feet.

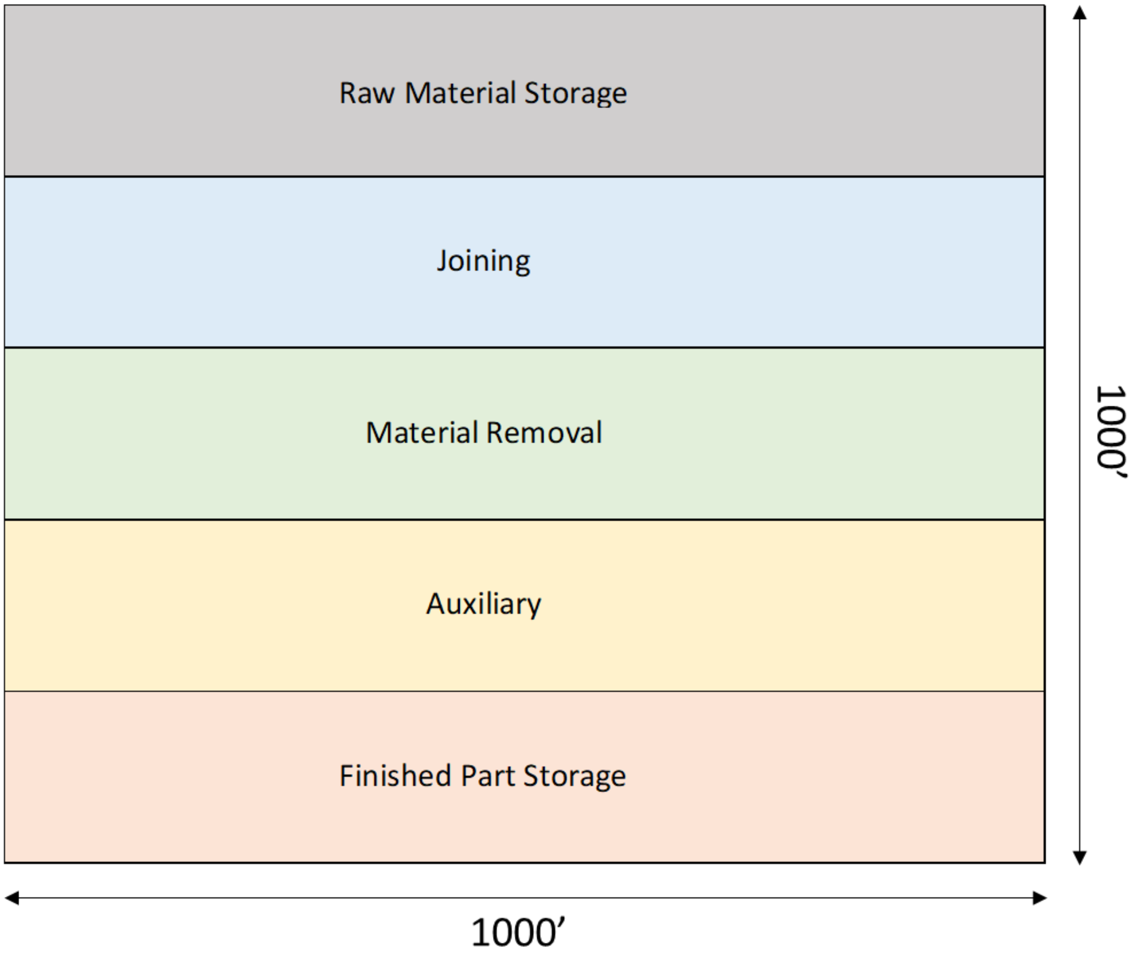


Figure 2: 1000' x 1000' Facility

As with the low-level material handling cost per unit move, these values will be inserted into Equation 1 in order to attain the material handling cost per move value that will be used. Based on the above factors, a value of $37.50 will be used. Like with the low-level material handling cost, a more detailed look at the computation and layout can be found in Appendix C.

4.5. Experimental Design

This research will use a two-level fractional factorial design in evaluating for which factor levels the assumption of an arbitrary layout is likely to lead to error during process plan generation. In order to evaluate the different factors, an experimental design (or DOE) is used to change one or more factors levels at a time in order to observe the effect that each factor has (*NIST/SEMATECH e-Handbook of Statistical Methods*, 2012). This research will use a two-level design to evaluate the effect of each factor. A two-level design means that each factor will only have two levels: a high-end value and a low-end value (*NIST/SEMATECH e-Handbook of Statistical Methods*, 2012). When referring to these factors, the high-end value will be notated with a "1", while the low-end value will be represented with a "-1."

This research uses seven factors, which were described previously. A full factorial design for this experiment would entail 2^7, or 128, different combinations of these factors. Each combination of these different factors will be referred to as a treatment combination. As testing all of these combinations for both part geometries would entail 256 total runs, a fractional factorial design is used to reduce the number of runs required. A fractional factorial design uses a carefully chosen fraction of the treatment combinations that would be tested in a full factorial design (*NIST/SEMATECH e-Handbook of Statistical Methods*, 2012). A method is then used to objectively select 32 different treatment combinations from among the different factor levels, so that the factor space can be covered efficiently and effectively (*NIST/SEMATECH e-Handbook of Statistical Methods*, 2012). Notably, this design assumes that three-order and higher interactions between variables are minimal. This research uses a 2^{7-2} design, which has 32 different combinations. This means that 32 runs will be performed for each of the tested part geometries. For each of these runs, the ten lowest cost configurations will be extracted for analysis. If fewer than ten configurations are available for a run, then as many as possible will be extracted. More information on experimental designs can be found in either: the Engineering Statistics Handbook, Design and Analysis of Experiments, or Statistics for Experimenters (Box, Hunter, & Hunter, 2005; Montgomery, 2012; *NIST/SEMATECH e-Handbook of Statistical Methods*, 2012).

4.6. Description of Factors

These factors used in this experiment were identified from the cost models present in Katana. The seven factors that will be tested are:

- Material Cost
- Material Removal Rate
- Part Volume
- Possible blank Types
- Load/Unload Time
- Joining Rate
- Labor Rate

This section will describe each of the above factors in detail. An explanation for how the factor will be tested and with which values will also be conveyed. A condensed version of this information can be found in a table in Appendix D.

4.6.1. Material Cost

The value will be presented in units of dollars per pound to isolate material cost from a part's size. This value will be tested with both a high-end and low-end value to simulate opposing manufacturing scenarios. Titanium is an expensive metal to manufacture and its market price will reflect this. Thus, the current North American market value of titanium, or more specifically Ti-6Al-4V, will be used as the high-end value for this factor. This price is approximately $26.00 per pound, as of July 25, 2018 ("MetalMiner Prices," n.d.-b). In order to accurately model this material cost, the density value will be adjusted to the density of Ti-6Al-4V within the Katana software to get an accurate material cost per unit volume. This density is 0.16 lb/in^3. This factor level will simulate manufacturing scenarios characterized by expensive material costs as seen in the aerospace industry, defense industry, and tech industry, among others.

Conversely, it is important for the low-end material cost value to represent situations where raw materials are relatively inexpensive purchases. Thus, the low-end value should represent materials are on the lower end of market prices. A-36 plate carbon steel is one of the lower cost metals available. Because of this its current market price will be used to represent the low-end value. The current North American market price is approximately $0.40 per pound, as of July 25, 2018 (“MetalMiner Prices,” n.d.-a). As with the high-end value for this factor, the density value in Katana will be adjusted for this factor to accurately simulate this material cost. This density value is 0.28 lb/in^3. This factor level will be used to simulate manufacturing scenarios characterized by inexpensive material costs such as the foil industry and clothing industry, among others.

4.6.2. Material Removal Rate

This value is used during a part’s machining or finishing process. The material removal step is where a part is machined to its final desired dimensions. The lone exception is if pre-machining is required. In that case, a material removal process may appear earlier in the process plan. This process is one of the most important processes for manufacturing a part and can have a large impact on the configuration’s final cost. The material removal rate is the volume of material removed per minute. This means that if the material removal rate is high, then more material will be removed from the part per minute, meaning that the process will finish quicker.

To this end, a high-end material removal rate will be used to simulate situations where a mill or lathe can remove material from the part very quickly. Sinkora (2018) discusses new machining developments in the manufacturing industry and mentions Greenleaf's XSYTIN-1 cutting tool. In one application, this tool is able to achieve a material removal rate of 100 in^3/min (Sinkora, 2018). This is an extremely fast speed and will be used for the high-end value during the experiment.

Inconel is a material that can be difficult to machine, and thus often require slower material removal rates. One article mentions a new method for milling in Inconel 718 that can result in material removal rates of 2.4 in^3/min-4.0 in^3/min (Zelinski, 2010). However, under other circumstances, less advanced machinery or tighter tolerance requirements could make a slower material removal rate necessary. Thus, in order to simulate this type of situation, a value of 1 in^3/min will be used. Because this value is much lower than the high-end value, the material removal process will take much longer when this value is used.

4.6.3. Part Volume

A part's size is another important factor in cost calculations. The part's size affects the speed of joining processes, how much material will need to be removed during machining, and the cost of the raw materials. It is important to note that the part volume is a separate factor from the part's geometry, or shape. As such, the part's volume will be scaled up or down independently of its geometry. Each part will be scaled between two levels, a high-end value and a low-end value. This process will allow part to grow or shrink without affecting its shape. Part volume is not considered when determining if any specific type of process or material handling method is viable for a specific part. This is expanded on in Appendix G.

There will be two levels for the part volume factor. The low-end value will represent relatively small parts. This level will scale the part to a volume of 128 in^3 (or 0.007407 ft^3). The high-end value will represent relatively large parts, by scaling the parts to a volume of 216,000 in^3 (or 125 ft^3).

4.6.4. Possible Blank Types

The blank types that are available for specific configurations will ultimately affect how that configuration is manufactured. These effects include changes in potential joins, variations in material cost, changes in machining cost, number of processing steps, and whether pre-machining is required for that part. Because of this it is important to test different types of blank types to simulate scenarios where certain blank types may not be available. A list of the different blank types that will be tested is show below:

- Rectangular Bar Stock: A blank that comes in a rectangular shape, such as a block or square.
- Circular Bar Stock: A blank that comes in a circular shape, such as a circular rod or a cylinder.
- Waterjet Plate: A blank that has been modified using a waterjetting process. This process allows the blank to take on more abnormal shapes. Using this process, a blank may be able to reach a shape close to the final part's shape. However, the waterjetting process is not fine enough to result in a perfect imitation of a part's shape. Because of this, the part will still need to be machined further during the material removal process.

Two different sets of these blank types will be used to simulate different manufacturing scenarios. The first set, or low-end scenario, will only include the rectangular bar stock and circular bar stock blank types. These are the more arbitrary blank types that offer little customizability and come in a specific shape. Because of this, the manufacturing scenario using these blank types will be more limited in how efficiently it can match blank types to reduce processing and material costs.

The high-end scenario will allow for any of the three different blank types to be used as a raw material input. This means that the joining process will have much more flexibility and can utilize blanks that will drastically reduce machining costs or make new joins feasible. This set of blanks will represent a scenario where designers have more customizable blanks to use as raw inputs. This should allow costs to be reduced for most parts.

4.6.5. Load/Unload Time

Every joining and material removal processes requires that a part be loaded prior to the process being started and later unloaded after the process is completed. For the purposes of this project, the load and unload times will be combined into one factor so that it can be adjusted for the experiment. In reality, a part’s load and unload times are often influenced by the weight and size of the part. A heavier, or larger, piece will usually require more time to load and unload than a lighter, or smaller, part. This connection may allow inferences about the weight and size of part in certain manufacturing scenarios to be drawn later in the project. Auxiliary processes also possess a load and unload component to their cost. However, these process costs are modeled as fixed entities for the purposes of this project, so this factor will not affect the load and unload times of those processes.

The high-end level for this factor will be 60 minutes (or one hour) to simulate situations where extreme care or effort is required when loading and unloading the part. The low-end level for this factor will be five minutes to simulate situations where the load and unload processes can be completed very quickly.

4.6.6. Joining Rate

The joining rate will be modified to simulate manufacturing scenarios with efficient joining processes and manufacturing scenarios with inefficient joining scenarios. The faster the joining rate, the more likely it is that a part's optimal configuration will in turn contain a high number of joins. Conversely, a lower joining rate means that it is less likely that a part's optimal configuration will feature a high number of joins. A larger cross-sectional joining area will also increase joining time, while a smaller cross-sectional area will cause the inverse effect. It is difficult to find data on joining rates, so the numbers will be derived by observing videos of different processes. Inertia friction welding is one popular process that can achieve high joining rates. One video shows this process being performed with a circular piece of metal that has a radius of about 6 in (Manufacturing Technology Inc (MTI), 2016). The welding process takes about 15 second, which results in a calculated joining rate of about 3.8 in^2/sec (Manufacturing Technology Inc (MTI), 2016). Friction welding is still a relatively recent technology and future developments may result in a joining rate higher than what is observed in the video. In order to account for these types of situations, a value of 5 in^2/sec will be used as the high-end factor level.

Conversely, soldering is another joining technique that can be used to join two pieces together. However, this technique is generally slower than friction welding. One video shows a man soldering two thin pieces of copper together with a lap joint (George Goehl, 2012). In this video, the cross-sectional joining area can be estimated to be about 1.5 in^2 and the process takes about 90 seconds to complete (George Goehl, 2012). This results in a joining rate of 0.0167 in^2/sec. This value will be rounded down, so that the low-end joining rate is 0.01 in^2/sec.

As mentioned, the joining rate depends on the cross-sectional area of the parts being attached. There are practical and theoretical limits on this area; more information on these limits can be found in Appendix A.3. For the purposes of this research, there is no limit on cross-sectional joining area.

4.6.7. Labor Rate

Labor is required at all steps of the manufacturing process. This means that a lower labor rate will reduce costs for every single step in the process, while a higher rate will do the opposite. Because of this, a lower labor rate should make process plans with a high number of steps more feasible, while a higher rate will induce the opposite type of behavior. To simulate this condition, it will be modeled with both a high-end and low-end value. The low-end value will be the current minimum wage rate in Oregon. This is approximately $10.00 per hour as of July, 28, 2018 (Beleiciks & Bechtoldt, 2018). The high-end value will use the average hourly rate of a mechanical engineer. This will simulate scenarios where the manufacturing of a part requires highly skilled labor. The Bureau of Labor Statistics reports a current average hourly wage rate of approximately $44.00 per hour ("Mechanical Engineers," 2017)

4.7. Different Part Geometries

Different part geometries can influence the relevance of certain factors. To account for this, the experiment will be ran twice with different part designs. These part designs have been chosen in an attempt to minimize the effect of varying part designs on the conclusions that can be drawn for the factors in this research. Accounting for these differences is an inherently subjective process, but an explanation for why these two specific parts were chosen will be given.

One of the things that must be accounted for are differences in a part's joining potential. Joining potential is solely determined by the part's geometry, independent of its volume, or size. A part's joining potential can best be described by looking at the number of protrusions that the part’s shape contains. A protrusion means that there is a potential joining point where the protrusion is connected to the rest of the part. This is an inherently subjective measure and is thus subject to some amount of error. Typically, a high number of protrusions means that more joins are likely to be feasible for that part, when compared to a competing geometry with a low number of protrusions. Thus, in order to account for these differences in joining potential, a part with a high number of protrusions will tested, as well as a part with a low number of protrusions.

The ultimate cost of manufacturing a specific part is also affected by that part’s geometry. Certain parts may have geometric complexities that require pre-machining. This allows certain features to be machined, before they become unreachable. If a part requires pre-machining this will increase the total cost of the part, as the material removal process must now be performed at least two times. This results in more setups and material handling moves, and thus a higher cost. Certain part geometries will also have higher joining and material removal costs because of their design. A larger cross-sectional area for a joining process will result in a higher joining cost for that specific join. Thus, if a part’s cross-sectional areas at its joining points is comparably large, then it will have a higher joining cost. This is difficult to predict and will not be accounted for explicitly. Instead, it will be accounted for by choosing two parts with different geometric characteristics.

Certain parts will require more material removal to reach their final designed shape. The amount of material removal required is determined by the fit between the blanks used and the final part design. Predicting the amount of material removal that will be required for a part geometry is difficult, and accounted for by using two different parts. Depending on the number of joins used, the available blank types, and the part volume, both parts will have configurations where the blanks match the final design well, and configurations where the blanks match the final design poorly.

The first part that will be tested has fewer protrusions, and thus a lower assumed joining potential. It is important to note that just because a part may only have a few joins in its optimal configuration, does not mean that the cost savings derived from the joining process will be minimal. In fact, the cost savings may be larger than some parts that have many joins because of how a singular join reduces material waste significantly. The first part that will be used is shown in Figure 3.

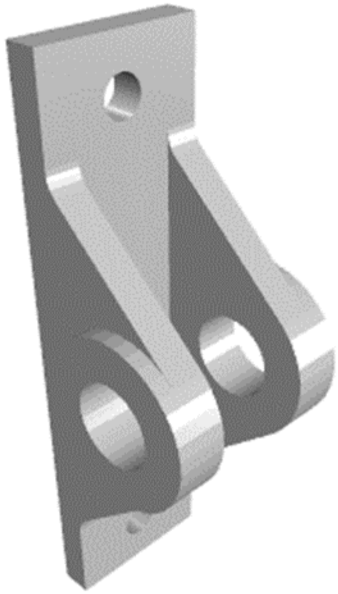


Figure 3: The "Bearing Block" part used to represent low-end joining potential.

The next part has more protrusions and, thus a larger assumed potential. This part is also composed of more complex geometry, which would lead to a large amount of material waste if it were to be simply machined out of a singular blank. The complex geometry does not necessarily result in greater joining cost savings than simpler parts, but means that there is likely to be a higher number of joins in the optimal configuration. The second part is pictured below in Figure 4.

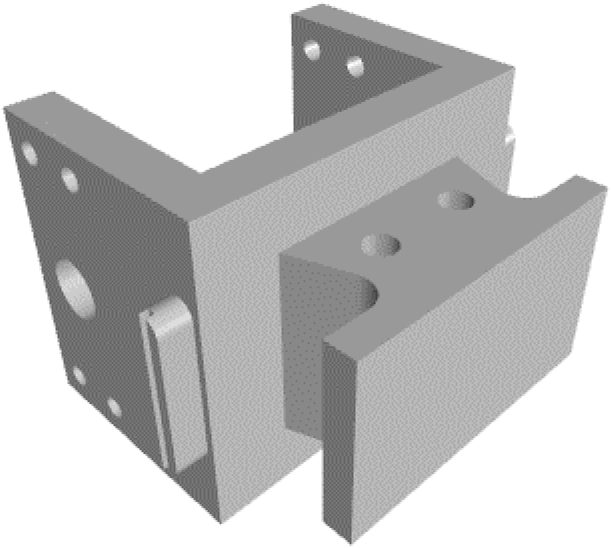


Figure 4: The "Square Support" part used to simulate high-end joining potential.

4.8. Numerical Responses

In order to accurately quantify the layout question, four numerical responses will be used. Two of these responses will measure how configurations differ in their rankings between the low high-level material handling costs. The other two responses measure how much the cost of configurations changes between the low and high-level material handling costs.

4.8.1. Correlation Responses

The first two responses quantify configuration ranking changes that can occur when changing the material handling cost. This is illustrated with the use of a bump chart, a tool that can be used to visualize changes between different material handling costs.

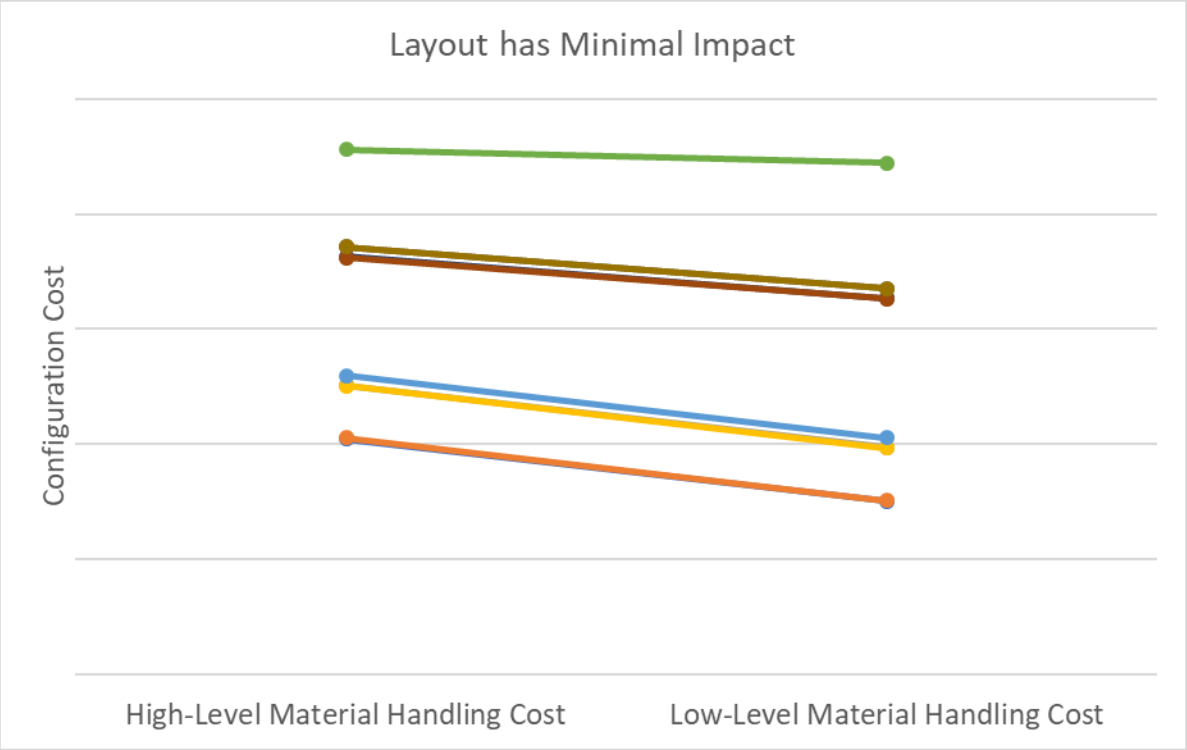


Figure 5: A bump chart illustrating a situation where the layout will likely have minimal impact on which configuration is chosen to be manufactured

Figure 5 illustrates a situation where the layout is likely to have a minimal impact on which configuration is chosen to be manufactured. The graph shows a plot of configuration costs for a hypothetical part. This total cost is calculated twice: once with a high-level material handling cost which are the points plotted on the left side of the graph, and once with a low-level material handling cost which is depicted by the points plotted on the right side of the graph. Because the lines in the graph are all relatively parallel and the rankings do not change between the two material handling scenarios, this can be said to represent a situation where the assumption of an arbitrary layout during process plan generation is not likely to lead to error in selecting a configuration. A bump chart showing the opposite type of situation is shown in Figure 6.

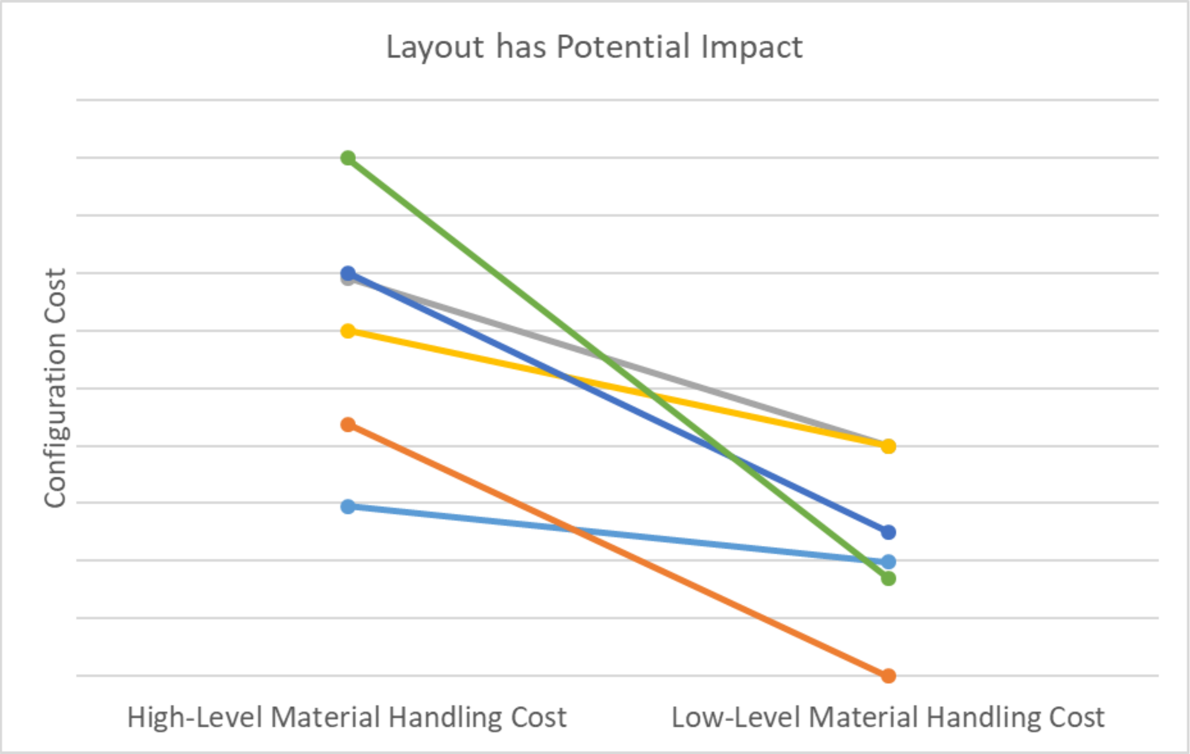


Figure 6: A bump chart illustrating a situation where the layout will have likely an impact on which configuration is chosen to be manufactured

Figure 6 illustrates a situation where the layout will likely have an impact on which configuration is chosen to be manufactured, because several lines cross and the rankings differ between the two material handling scenarios. This means that a configuration that is optimal to manufacture for one layout may no longer be optimal in the other layout. Because of this, layout optimization may need to be incorporated into the process planning process to ensure optimality for the selected configuration.

The goal of the two correlation responses is to quantify on a continuous scale the different types of behavior exhibited in these two graphs. Two correlation responses were utilized because of the type of behavior exhibited in the graphs. Rank correlation alone fails to account for situations where the cost rankings may change, but the costs are close enough that they are well within the margin for error, given the cost model precision. The percentile correlation accounts for the amount of cost change. A more detailed description of both these responses will be given in the following paragraphs.

4.8.1.1. Rank Correlation

The rank correlation measure is computed by ranking all of the configurations for a treatment combination from cheapest to most expensive for both the low-level and high-level material handling scenarios. The linear correlation between these two rankings is then computed and used as a numerical response. This measure objectively shows if the rankings for a certain part differ based on the type of material handling scenario.

4.8.1.2. Percentile Correlation

The percentile correlation is calculated by first converting the raw cost values in both material handling scenarios to percentile values. This is done with Equation 2 below:

Equation 2: Percentile Conversion Equation

$$Percentile\ Value = \frac{(Raw\ Cost\ Value - Minimum\ Cost\ Value)}{(Maximum\ Cost\ \ Value - Minimum\ Cost\ Value)}$$

The terms in Equation 2 are explained below:

- *Percentile Value*: The scaled output value that the raw cost value (which is the input) will be converted to.
- *Raw Cost Value*: The configuration's cost input for that material handling scenario that will be converted to the percentile value.
- *Minimum Cost Value*: The minimum cost value within the material handling scenario's set of cost values.

- *Maximum Cost Value*: The maximum cost value within the material handling scenario's set of cost values.

The linear correlation is then computed with the percentile values from both material handling scenarios. This response shows if the configurations change ranks, but also reflects the magnitude to which the costs have changed. An example of how these values are computed can be seen in Appendix F.

4.8.2. Percent Change Responses

The next set of responses quantifies the amount increase in cost that a configuration experiences between the low-level material handling scenario and the high-level material handling scenario. However, the magnitude of this difference is not particularly relevant. What is more important is the percent change that the configuration experiences. For example, a $2000 configuration in the low-level material handling scenario may have a cost of $2100 in the high-level material handling scenario. Another configuration may have a cost of $100 in the low-level material handling scenario, but a cost of $200 in the high-level material handling scenario. In both scenarios, the cost difference between the two material-handling scenarios is $100. However, the importance of this difference is much higher in the second example. This is because the percentage difference is much higher in the second scenario.

The material handling cost will have some variance within it. If the percent difference between the two material handling scenarios is high, then this means that there is an opportunity for this variance in the material handling cost to cause error when choosing what configuration to manufacture. In the scenario above, it is much more likely that an error in estimating the material handling cost will have an impact in the scenario with the higher percentage difference.

This is because the material handling cost composes a higher portion of the configuration's total cost in this scenario.

The percent change for each configuration is calculated with Equation 3.

Equation 3: Percent Change Calculation

$$Percent\ Change = \frac{(HighLevel\ Material\ Handling\ Scenario\ Cost - LowLevel\ Material\ Handling\ Scenario\ Cost)}{LowLevel\ Material\ Handling\ Scenario\ Cost}$$

The first response in this category is the average percent change between material handling scenarios for the specific manufacturing scenario. This gives an objective measure for how variance in the material handling cost can impact what configuration is chosen to manufacture. In this research, cost is used as the sole deciding measure in determining which process plan to select; thus, the lowest cost, or optimal, configuration, will always be the selected process plan. Because of this, the optimal configuration's percent change is used as the second percent change response. A more detailed computation of these factors can be seen in Appendix F.

4.9. Analysis of Experimental Results

Well-established methods for two-level designs will be used to compute effect estimates, using the contrast of the responses (Montgomery, 2012). An important factor is defined in this research as a factor that has a large effect on whether the assumption of an arbitrary layout is likely to lead to error. In order to determine each factor's importance, the estimates for each factor and all of its interactions will be plotted on normal probability plots. If an effect or interaction is not an important factor, then it should only have a noise effect on the response. Noise effects are assumed to be observations from a normally distributed random variable.

Because of this, when an effect or interaction only appears as noise, then it will plot on a normal probability plot near where a fitted linear line would go. Thus, if any point on the graph is not near where the fitted line would go, then it can be concluded that the effect is an important factor. An example of this behavior can be seen in Figure 7. The outlier points circled in red would be evaluated as important factors.

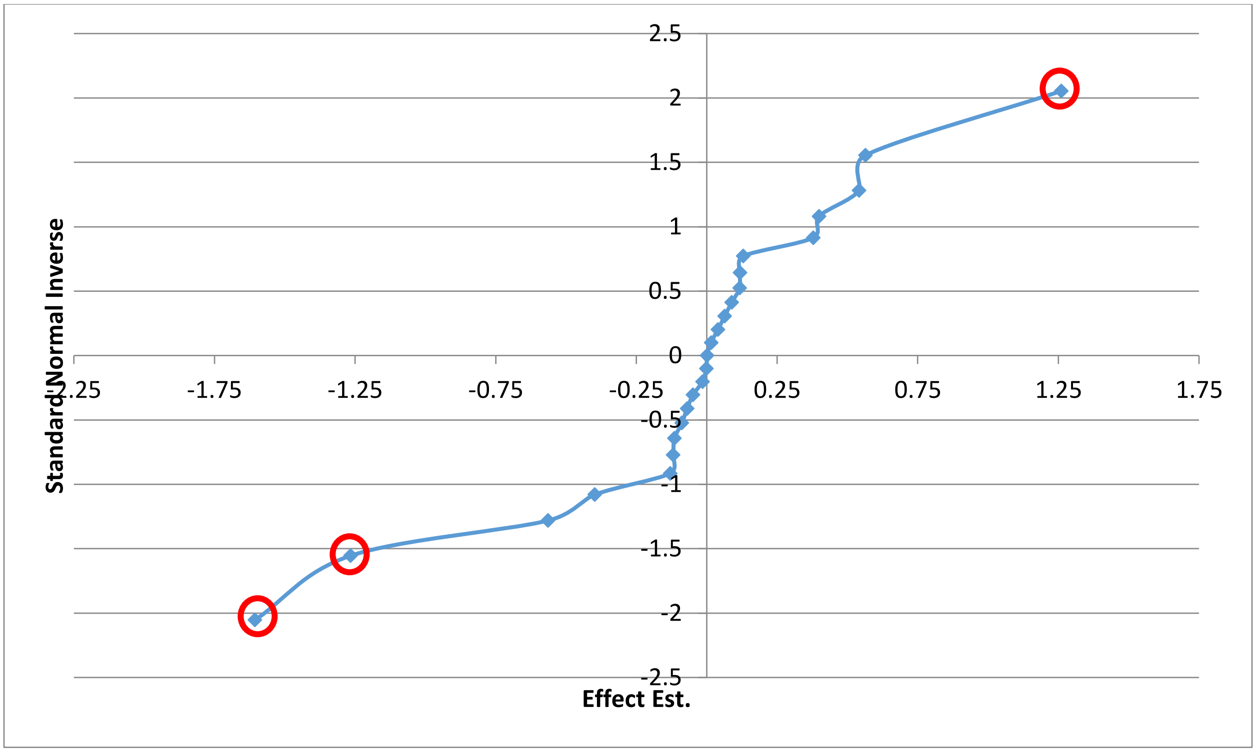


Figure 7: Normal probability plot illustrating outlier points

Once the above analysis is performed, a further inspection of the factors deemed important will be conducted to determine whether the high-end or low-end factor level is influencing the assumption of an arbitrary layout. In order to do this, data will be analyzed for each of the situations where a relevant factor is at its high-end or low-end value within the tested combinations. Averages will be computed for all numerical responses for each of these high-end and low-end values. These averages can then be compared to determine if a factor's relevance comes into play based on its high-end or low-end value. The mean is selected as the centralized measure, to account for the fact that more extreme values are relevant in determining whether particular combinations are relevant.

Next, the combinations of relevant factors in the tested treatment combinations will be analyzed to determine which of these various combinations have situations that could cause the assumption of an arbitrary layout to be unreasonable. In order to determine if the assumption is reasonable for these combinations, averages of the numerical responses will be calculated for each combination. For the same reasons as above, the mean will be used instead of the median or mode. The means will be calculated for both tested parts, so that it can be determined if part geometry affects the relevance of certain combinations. Finally, the combinations will be categorized into three different classes:

1. Situations where it is critical that the layout be accounted for in process plan generation because the assumption of an arbitrary layout is completely unreasonable.
2. Situations where considering the layout during process plan generation is important for optimality, but the assumption of an arbitrary layout is unlikely to lead to significant amounts of error.
3. Situations where the layout assumption is reasonable, and the layout does not need to be considered in process plan generation.

5. Results

The experiment was conducted under a number of assumptions that have been previously discussed. A concise summary of these assumptions can be found in Appendix G.

Responses were obtained for all 32 treatment combinations with both tested parts. These results and the corresponding normal probability plots that were used to determine which factors are important can be found in Appendix H. Four factors were found to stand out. These factors were almost identical between the two tested part geometries. There was one factor that differed in its effect between the two parts. The near similarity in factor effects between the parts implies that the part geometry is not having a large impact in determining which factors are important. This could be a symptom of the small number of parts that were tested, however, and more varied geometries would need to be tested in order to conclude this with absolute certainty.

5.1. Important Factors

The four important factors did vary based on the response. Two factors were clearly more important for the two correlation responses. A normal probability plot for the bearing block part effects can be seen in Figure 8.

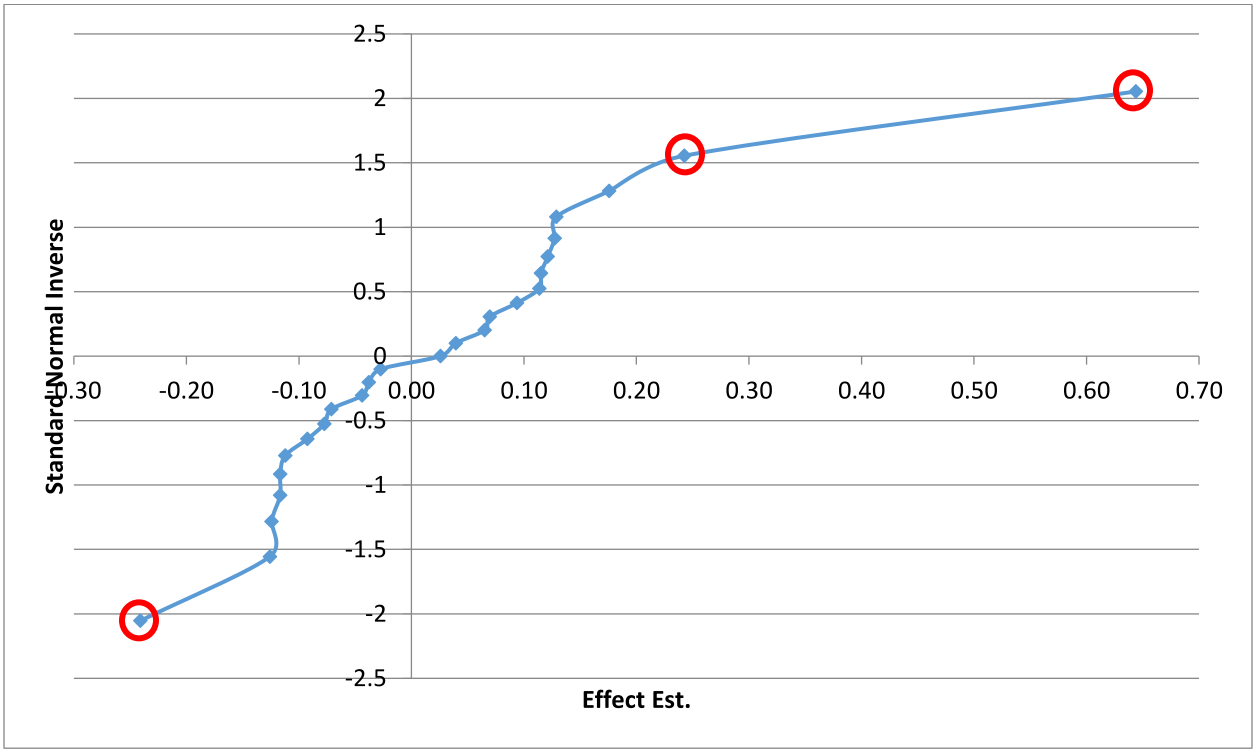


Figure 8: Normal probability plot of effects of the rank correlation response for the bearing block part

There are notable outliers on this chart that are highlighted in Figure 8. The highlighted points are in order from left-to-right:

- The interaction between the load/unload time factor and the part volume factor
- The load/unload time factor
- The part volume factor.

The normal probability plot for the percentile correlation response with the bearing block part shows similar points as outliers. However, as mentioned above, there was a difference in outliers between the bearing block part and square support part. One of the plots for the square support part can be seen in Figure 9. The rest of the charts for both this part and the bearing block part can be found in Appendix H.

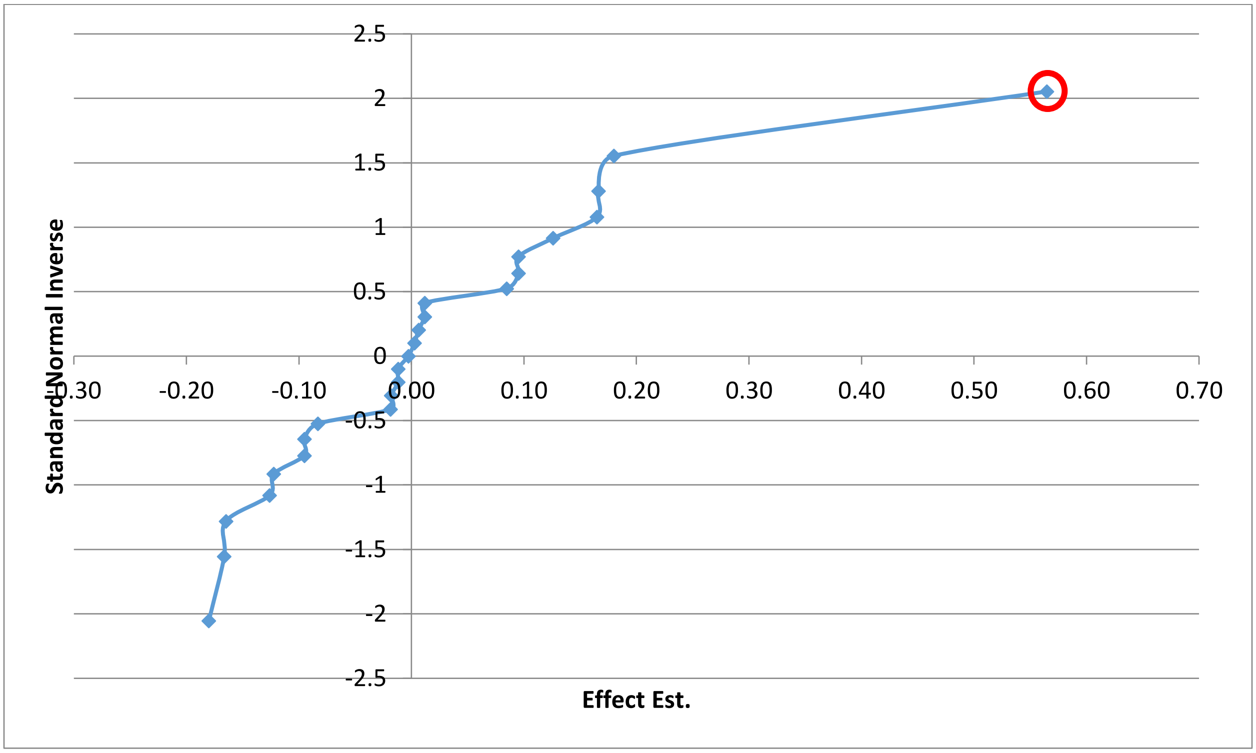


Figure 9: Normal probability plot of effects of the rank correlation response for the square support part

The outliers in this chart are different from the outliers in the bearing block chart. There is only one clear outlier in this chart, which is the part volume response. This point is highlighted in red above in Figure 9. This is an interesting difference and it is not apparent why the load/unload time response appears as an outlier for the bearing block part, but not for the square support part. The effect estimate for the load/unload time factor is slightly lower for the square support part, so there is something about that part's geometry which causes the factor to be less important. The primary difference between the parts is that the square support has more protrusions and is a more complex part. So, it is possible that the difference in factors is because the square support part requires more material removal or because the part has a higher tendency to use high number of joins in its generated process plans.

The percent change responses show other factors being important as well. Unlike the correlation responses, the charts were similar across both parts and for both types of percent change responses. An example is presented in Figure 10. The rest of the plots can be found in Appendix H.

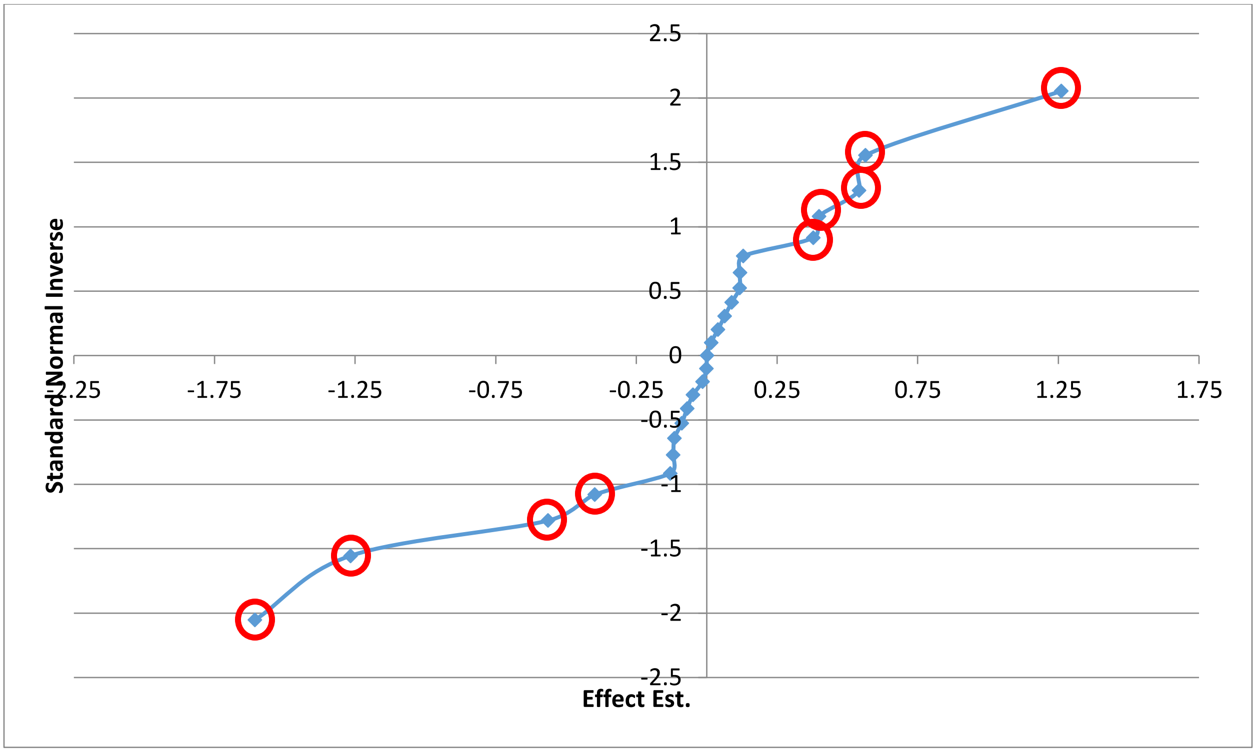


Figure 10: Normal probability plot of effects of the average percent change response for the Bearing Block Part

As with the correlation charts, there were noticeable outliers on the percent change charts that were common across all of the charts. From left-to-right the highlighted points in Figure 10 are:

- The part volume response
- The material cost response
- The labor rate response
- The load/unload time response
- The interaction between the load/unload time and material cost responses
- The interaction between part volume and the load/unload time responses
- The interaction between the material cost and labor rate responses

- The interaction between the part volume and labor rate responses
- The interaction between the material cost and part volume responses

From these charts, the material cost and labor rate factors also stand out as outliers. The percent change factors are less relevant to the layout question at hand than the correlation responses. Because of this, it was concluded that the material cost and labor rate are also important, but to a lesser degree than either the load/unload time and the part volume factors.

In summary, the part volume, load/unload time, labor rate, and material cost of a manufacturing scenario are all important to the layout question. Part volume is by far the most important factor. Load/unload time is the second most powerful factor. The remaining two factors are less important than load/unload time, with the labor rate and material cost factors probably being of about equal importance.

5.2. Important Factor Levels

The next step examined whether it is at the high-end or low-end values for a certain factor where the assumption of an arbitrary layout is likely to lead to error in selecting which configuration to manufacture. To assess this, averages for each response were computed for all of the treatment combinations with a low-end factor value. The same process was then repeated for the high-end factor value. Statistics were also calculated for both part geometries. For example, to assess the part volume factor, all of the scenarios were selected where that factor had a low-end value in the treatment combination. The mean was then computed from all these situations for all four numerical responses. This same process was then repeated for the high-end part volume level.

The results for the Bearing Block part are in Table 1 and the results for the Square Support part are in Table 2:

Table 1: Bearing Block Responses for different factor levels

Factor Name	Factor Level	Average Rank Correlation	Average Percentile Correlation	Average Percent Change	Optimal Configuration Percent Change
Part Volume	High-End	1.00	1.00	0.32%	0.57%
	Low-End	0.35	0.53	160.95%	157.08%
Load/Unload Time	High-End	0.80	0.83	60.72%	49.68%
	Low-End	0.55	0.70	100.55%	107.97%
Material Cost	High-End	0.58	0.76	16.29%	21.16%
	Low-End	0.73	0.72	143.97%	135.17%
Labor Rate	High-End	0.70	0.77	52.41%	49.46%
	Low-End	0.66	0.76	108.86%	108.18%

Table 2: Bearing Block Responses for different factor levels

Factor Name	Factor Level	Average Rank Correlation	Average Percentile Correlation	Average Percent Change	Optimal Configuration Percent Change
Part Volume	High-End	1.00	1.00	0.34%	0.77%
	Low-End	0.44	0.57	174.23%	179.01%
Load/Unload Time	High-End	0.80	0.81	61.10%	61.15%
	Low-End	0.64	0.76	113.48%	118.63%
Material Cost	High-End	0.68	0.84	19.75%	25.39%
	Low-End	0.71	0.68	153.59%	152.80%
Labor Rate	High-End	0.77	0.80	59.69%	61.15%
	Low-End	0.67	0.77	114.89%	118.63%

5.2.1. Part Volume

From this data, some conclusions were supported about the important factor levels. First, it is clear that part volume is by far the most important factor. When the part volume is at its high-end value, the assumption of an arbitrary layout does not lead to incorrect decisions. The percent change responses are also very low, meaning that the cost does not change much between material handling scenarios. On the other hand, when the part volume is at its low-end value, the correlation response values are very low. In addition, the percent change responses are higher. Together, this signifies that with a low-end part volume the assumption of an arbitrary layout should be questioned. These observed effects are the same across both parts indicating that this conclusion may not be affected by part geometry. As mentioned above, these conclusions do assume that a part's cost increases with its volume. This relationship may not be present for certain manufacturing environments, like micromanufacturing.

5.2.2. Load/Unload Time

The high-end load/unload time is relatively steady at approximately a value of 0.8 for both correlation responses and across both parts. This implies that a high load/unload time value will be more likely to promote situations where the assumption of an arbitrary layout is reasonable. However, there may be certain manufacturing scenarios where the assumption is not reasonable, given the combination of other factors present in that scenario.

The effect of the load/unload time low-end value is the same across both part geometries, but the magnitude of the effect differs. With the bearing block part, there is a noticeable decrease in the correlation responses with the low-end load/unload time. With the square support part, there is a is also a decrease in the correlation responses, however, it is of a much smaller magnitude. This difference between the parts isn't large enough to dismiss the load/unload time as an important factor, but does line up with the conclusions that were drawn previously with the normal probability plots.

The percent change differences are more similar across both parts, with noticeably higher responses for the high-end load/unload time values. In conjunction with the differences noted above for the correlation responses, it can be concluded that the low-end load/unload value is more likely to promote situations where the assumption of an arbitrary layout may lead to error in selecting a configuration. As the differences are less extreme than with the part volume factor, it can also be concluded that the load/unload time factor is a less important factor.

5.2.3. Material Cost

The material cost factor presents conflicting data within the correlation responses. With the bearing block part, the high-end value is noticeably lower for the correlation response. However, the percentile correlation responses are very similar between high-end and low-end values. This implies that the configuration rankings do change for many of the treatment combinations with the high-end value. However, these changes must be relatively minor, since the percentile correlation response does not exhibit the same effect as the ranking correlation. For the square support part, a similarly conflicting situation occurs. This time the low-end value exhibits a noticeably lower percentile correlation than the high-end value. However, the rank correlation values are very similar. A clearer picture is illustrated by the percent change values. For both of the percent change values, there is a relatively significant increase from the high-end value to the low-end values. This change is similar across both parts.

The conflicting information described above makes it more difficult to draw conclusions on the effects of the material cost factor. None of the average response values are extreme so it can be concluded that there could be situations where the assumption of an arbitrary layout is either reasonable or unreasonable for both the high-end and low-end values. Based on the percent change responses, it seems reasonable to conclude that the low-end material cost value is the more likely value to cause a situation where the assumption of an arbitrary layout is likely to lead to error in selecting a configuration to manufacture.

However, based on the nature of the material cost factor, it is understandable why conflicting information in the responses would occur. A low material cost value will result in a reduction of the total manufacturing cost, thus making the material handling cost compose a larger portion of the part's cost. On the other hand, a high material cost, will promote more joins within process plan generation. This will cause more material handling moves, thus increasing the material handling cost, and increasing its importance within the material handling scenario. Based on all of this, it can be concluded that the low-end material cost is more likely to promote a situation where the assumption of an arbitrary layout is unreasonable. However, depending on the combination of factors a high-end value could also promote the same type of situation. Because of the somewhat conflicting results, this factor seems to be less important than either of the two factors discussed previously.

5.2.4. Labor Rate

The labor rate factor presents mostly homogenous behavior within its mean response values. The correlation responses present no difference between the high-end and low-end values, so it is hard to conclude anything definitive based on the pair of correlation responses. On the other hand, there is a distinct increase in the percent change factors from the high-end value to the low-end value. This shows that the cost of manufacturing a part will be noticeably lower with a low-end labor rate. So, it is likely, that a low-end labor rate value promotes a manufacturing scenario where the assumption of an arbitrary layout is more likely to lead to error when selecting a configuration. Because this inference is only apparent from the percent change responses, this factor is probably of similar importance to the material cost factor.

5.2.5. Relative Importance of Factors

From the above analysis, it was concluded that all four of the previously referenced factors are important to the layout question. However, these factors are also of differing importance with some factors affecting the layout question more than others. The factors are ranked in order of importance below:

1. Part Volume
2. Load/Unload Time

3-tie. Material Cost

3-tie. Labor Rate

5.3. Analysis of Manufacturing Scenarios

As mentioned, above the assumption of an arbitrary layout is reasonable when the part volume is at its high-end value. Because of this, it is not necessary to analyze any situations where the part volume is at the high-end value. It is already known that the eight combinations of important factors where the part volume is at its high-end volume will result in conclusions that state the assumption of an arbitrary layout is reasonable. The other eight situations where the part volume is at its low-end value were assessed further to determine if the assumption of an arbitrary layout is likely to lead to error in selecting a configuration. This assessment was done for both parts to determine if the differences in geometry had any effect in the conclusions that could be drawn. The data for these eight treatment combinations can be found in Appendix I.

The eight situations were categorized primarily based on their correlation response values. The percent change response values were also incorporated into the analysis, but are less important. For this analysis the scenarios were divided into three categories:

1. Situations where it is critical that the layout be accounted for in process plan generation because the assumption of an arbitrary layout is completely unreasonable.

2. Situations where considering the layout during process plan generation is important for optimality, but the assumption of an arbitrary layout is unlikely to lead to significant amounts of error.
3. Situations where the layout assumption is reasonable, and the layout does not need to be considered in process plan generation.

5.3.1. Manufacturing Scenario 1

The factor levels for this scenario can be found in Table 3 and the statistics can be found in Table 4.

Table 3: Scenario 1 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	1	1	1

Table 4: Manufacturing Scenario Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.62	0.39	28.98%	21.93%
Square Support	0.82	0.77	32.45%	28.94%

The first manufacturing scenario is one of two scenarios, where there is a relatively large difference in response values between the two tested part geometries. The bearing block geometry has a relatively middling rank correlation, but a very low percentile correlation. On the other hand, the square support part has a relatively high value for both its percentile correlation and rank correlation values. Because of the mixed values for this scenario, this scenario was categorized within the second category. It is necessary to consider the layout during process plan generation for this combination if optimality is desired, but failing to consider the layout is unlikely to lead to drastic error in selecting a configuration to manufacture. It is likely that the necessity of considering the layout during process plan generation will depend on the geometry of the part being considered.

It is not completely clear why there is such a noticeable difference between the two parts for this scenario. However, it was hypothesized that the high material cost caused a high number of joins to be used during process plan generation. Because the square support has a higher number of protrusions, there were many different combinations of joins that were suitable for this part. On the other hand, because the bearing block has a lower number of protrusions there were a limited number of configurations where a high number of joins could be selected. This forced some low join configurations to be considered during process plan generation, and naturally introduced more situations where a variance in the material handling cost could affect the configuration rankings. More research would be needed to conclusively determine the reason for this.

This situation is something that could be found in certain types of real-life manufacturing scenarios. The low part volume and high material cost means that the parts being manufactured would be of a relatively moderate size and come from expensive raw material. The high load/unload time also implies that the parts are either difficult to machine and require intricate machinery, fragile, extremely heavy, or hazardous. The high labor rate value also means that the parts are manufactured by workers who are either very skilled or work in hazardous conditions.

One plausible manufacturing scenario seems to be the manufacturing of hazardous or fragile moderately-sized defense parts. The manufacturing of defense parts can occasionally require skilled labor if, for example, precise CNC machining is required. Certain defense parts could also be hazardous, if radiation or explosives are involved. Defense parts also, generally, require precise tolerances and may come from a heavy material like titanium. Many of the materials used in the defense industry are also very expensive. Defense manufacturing can also occur in situations where a large quantity of parts is produced. The efficiency of material handling processes becomes more important with larger production volumes. If the part production quantity is large enough to make material handling efficiency important, it would probably be wise to consider the layout during process plan generation for a scenario like the one described.

Another application could be the manufacture of moderately-sized high-end luxury goods. These goods could require extreme precision and be made from very expensive materials (e.g. gold or another precious metal). This precision would require skilled labor. Because of their luxury nature, the goods would also have to be handled very carefully which would make a large load/unload time value reasonable. However, this type of scenario is extremely unlikely to produce much more than a small quantity of parts per year. Because of this, material handling efficiency would be a rather minor issue comparatively. For this type of situation, it would probably only be necessary to consider the layout during process plan generation if absolute optimality is desired.

The manufacture of moderately-sized aerospace parts could also fit within this scenario. Some of the parts within this industry are either hazardous or require precision, making skilled labor a reasonable assumption. Because of this precision, these parts will probably require a high/load unload time to ensure that they are not damaged. Intricate machinery is also occasionally used which sometimes has higher load/unload times. Many aerospace parts are created from titanium or another expensive material, making the a relatively high material cost likely in this industry. However, this industry is unlikely to have a large production volume, making material handling efficiency less important.

5.3.2. Manufacturing Scenario 2

The factor levels for this scenario can be found in Table 5 and the statistics can be found in Table 6.

Table 5: Scenario 2 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	1	1	-1

Table 6: Scenario 2 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.18	0.66	36.33%	52.06%
Square Support	0.41	0.70	45.69%	52.44%

Unlike with the previous scenario, the statistics do not vary significantly between the two different part geometries. Both parts have low rank correlation values, although the bearing block's correlation is significantly lower. And both the parts have relatively middling percentile correlation values. This implies that this scenario is also best categorized into the second category. It is necessary to consider the layout during process plan generation for this combination if optimality is desired, but failing to consider the layout is unlikely to lead to drastic error in selecting a configuration to manufacture. Unlike with the previous scenario, it does not seem like the part geometry will have a significant impact on the reasonableness of the layout.

This combination also fits a type of scenario where defense parts are being manufactured. The only difference in this scenario is that the labor rate for this scenario is on the low-end, as opposed to the high-end. Certain defense part manufacturing scenarios are characterized by the situation discussed for the first treatment combination, but with a lower labor rate. These scenarios would still be characterized by moderately-sized parts that use expensive raw material and require a high load/unload time because of fragility or the use of intricate machinery. However, the labor would now be compensated with a low-end value, meaning the work required is no longer skill-intensive or hazardous. This situation could also be found in reality, and is even more likely to be in a situation than the previous scenario that requires a large production volume.

For similar reasons as above, the aerospace industry could also be characterized by these traits. However, the caveat is that the scenario would have to employ workers who are paid with a relatively low labor rate. This means that the specific parts being manufactured would have to not require skilled labor and not be hazardous. In addition, for material handling efficiency to be an important cost driver, the manufacturer would have to be producing a large quantity of these parts. As mentioned above, this condition seems unlikely, but it is possible that it could be met for some subset of aerospace manufacturing.

Finally, the moderately-sized computer electronics industry could also fit within this treatment combination. The manufacturing of products like heatsinks and memory use expensive materials, and are reasonably fragile, so care would need to be used when handling the products. This could lead to long load/unload times. The labor to produce these products does also not need to be highly skilled and the work is not hazardous. Because of this it is reasonable to expect that the labor is compensated with a wage more similar to the low-end value in this research than the high-end value. Many of these items are also produced on a large scale, so it is reasonable to expect a large enough part quantity in these industries to make material handling efficiency relevant.

5.3.3. Manufacturing Scenario 3

The factor levels for this scenario can be found in Table 7 and the statistics can be found in Table 8.

Table 7: Scenario 3 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	1	-1	1

Table 8: Scenario 3 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.05	0.73	35.62%	51.60%
Square Support	0.22	0.76	45.01%	62.44%

The third manufacturing scenario was also placed in the second category. While the rank correlation values are low for both parts, the percentile correlation values are reasonably high. This implies that the configuration ranks do change significantly between material handling scenarios, however the cost differences in these changes are not significant. The statistics are also similar across both parts meaning that the interpretations do not change between the parts. This combination was also placed within the second category. Because of this, it is necessary to consider the layout during process plan generation for this combination if optimality is desired, but failing to consider the layout is unlikely to lead to drastic error in selecting a configuration to manufacture.

The relatable manufacturing scenarios for this treatment combination are similar to the ones mentioned above. This treatment combination may occasionally be relevant for one of the above industries. However, they are probably better encapsulated by either the first or second treatment combination. The defense industry could have certain situations characterized by this treatment combination. However, that manufacturing scenario is more likely to have high load/unload times because the products are usually fragile, require precision, and may be hazardous. Finally, because of the delicate nature of its products the aerospace industry is also likely to be characterized better with high load/unload times. The computer electronics industry is also probably better modeled by the second manufacturing scenario. That industry is probably better modeled with a low-end labor rate than the high-end value.

5.3.4. Manufacturing Scenario 4

The factor levels for this scenario can be found in Table 9 and the statistics can be found in Table 10.

Table 9: Scenario 4 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	1	-1	-1

Table 10: Scenario 4 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.08	0.71	37.41%	54.08%
Square Support	0.33	0.92	44.66%	71.84%

The fourth manufacturing scenario is nearly identical to the third scenario. It is also characterized by very low values for the rank correlation response. However, again, the percentile response values are moderately high. Because of this, the second manufacturing scenario can also best be characterized by the second category. It is necessary to consider the layout during process plan generation for this combination if optimality is desired, but failing to consider the layout is unlikely to lead to drastic error in selecting a configuration to manufacture. There is a small difference in values for the parts, with the square support part having a higher value for both correlation responses. However, both sets of values are in the same approximate range, so the same conclusions would be drawn for each part independently.

The relatable manufacturing scenarios for this treatment combination are nearly identical to the third manufacturing scenario. The difference between the two combinations is that this treatment combination has a low-end labor rate value, while the third combination has a high-end labor rate. Like with that combination, there are probably a few relevant scenarios within the computer electronics, defense and aerospace industries. However, those industries are probably better characterized by a high-end load/unload value, because of the nature of their products. Thus, the first and second manufacturing scenarios are probably better characterizations of those industries.

The computer electronics industry could be applicable, but that industry is more likely to have high load/unload times, which are the opposite of the values in this treatment combination. The high-end moderately sized luxury goods industry may be one scenario that is best captured by this treatment combination. If the goods made for a particular scenario do not require extensive setups and are not prone to fragility, then this combination could serve as a better model of that situation. However, as mentioned above, the quantity of parts produced for such a scenario is likely to be so low that material handling efficiency is an irrelevant factor to the bottom line of the industry.

5.3.5. Manufacturing Scenario 5

The factor levels for this scenario can be found in Table 11 and the statistics can be found in Table 12.

Table 11: Scenario 5 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	-1	1	1

Table 12: Scenario 5 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.84	0.82	97.38%	45.44%
Square Support	0.82	0.68	92.02%	89.32%

This treatment combination had relatively high values for both correlation responses. These values differed slightly between the parts, but the differences were not large enough to affect the conclusions that were drawn for each part. Because of the relatively high correlation values for this combination, it was categorized within the third category. The layout for this treatment combination is unimportant, and it is not necessary to consider it during process plan generation. Because of this, no real-world manufacturing analogy will be drawn for this treatment combination.

5.3.6. Manufacturing Scenario 6

The factor levels for this scenario can be found in Table 13 and the statistics can be found in Table 14.

Table 13: Scenario 6 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	-1	1	-1

Table 14: Scenario 6 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.75	0.75	321.72%	275.70%
Square Support	0.35	0.32	317.21%	315.34%

Like with the first treatment combination analyzed, this combination experiences a notable difference in response values between the two tested part geometries. Because of the extremely low response values for the square support part, it is necessary to categorize this combination into the first category. The percent change values are less relevant than the correlation values, but are distinctly higher in this treatment combination than in any of the other combinations that were previously analyzed. These values are more constant across the two parts. Because of this, the combination was placed within the first category. Considering the layout during process plan generation is critical, and failing to do so could lead to a significant error in selecting the configuration to manufacture.

As mentioned above, there is a distinct difference in correlation response values between the two parts. Thus, the consideration of layout during process generation is dependent on the geometry of the part being manufactured. More testing would need to be done on different part geometries in order to determine with certainty why there is a difference between the two parts for this treatment combination. However, as with the first manufacturing scenario it is hypothesized that this difference comes from the material cost factor. The low material cost will increase the tendency for most configurations that are generated to have a low number of joins. The bearing block has fewer protrusions and is more suitable for low-cost, low-join configurations. On the other hand, the square support part has more protrusions and, thus, less suitable for low-cost, low-join configurations. Because of this, the square support part will still have some high-join configurations within its ten cheapest configurations. These high joins configurations will require a larger number of material handling moves when compared to the low-join configurations. The existence of both of these types of configurations for the square support helps explain why the square support part has lower values for its correlation responses. More research would need to be done in order to determine why this specific treatment combination has a larger difference between its parts than any of the other treatment combinations that also have a low-end material cost value.

Low to medium-end wood manufacturing of moderately-sized parts is one industry that this treatment combination has a possible connection to. For example, the manufacturing of items such as smaller furniture, smaller doors, and picture frames, are all items that would have a relatively low material cost. These items are also not hazardous and do not require skilled labor, so the labor could be compensated with a value similar to the low-end value. Finally, wood glue is a joining technique within the woodworking industry that has a relatively long load/unload time, so that factor level is representative of this joining process. These products can also be produced in high quantities making material handling efficiency an important consideration.

Another related industry could be the manufacture of moderately-sized metal goods that are made from cheaper metals, such as steel. Staplers, three-hole punchers, metal water bottles, metal grooming items (e.g. electric shavers), and some metal parts in the automotive industry would all fit in this category. These items would be correctly categorized with a low-end labor rate, as they are not hazardous and do not require skilled labor. However, the load/unload time could be higher than the value in this treatment combination, depending on what is specifically being manufactured. Thus, these situations may be better encapsulated by one of the two following scenarios. However, there may be specific situations where this specific treatment combination is a better fit. The products are produced in a large quantity, so material handling efficiency is important.

5.3.7. Manufacturing Scenario 7

The factor levels for this scenario can be found in Table 15 and the statistics can be found in Table 16.

Table 15: Scenario 7 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	-1	-1	1

Table 16: Scenario 7 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.07	0.19	256.15%	274.80%
Square Support	0.25	0.20	306.83%	305.74%

This treatment combination features very similar responses for both the square support and the bearing block parts. The correlation responses for both of these parts are very low, leading to this combination to be categorized in the first category like the previous combination. Considering the layout during process plan generation is critical, and failing to do so could lead to a significant error in selecting the configuration to manufacture.

The applicable manufacturing scenarios are very similar to the ones mentioned in the previous combination. The difference is that this combination features a low-end load/unload time and a high-end labor rate. It is difficult to fathom a scenario where a high-end labor rate would be used for one of the above scenarios, as none of the products are hazardous or require skilled labor. The one exception may be with moderately-sized wood manufacturing. There are higher end wood products that do required skilled labor. For example, hand-carved decorations of higher quality may use skilled labor. These products may use a value similar to the high-end labor rate. However, there is another caveat, in that these products would have to have low load/unload times. As mentioned above, the current joining process commonly used for wood products is wood glue. A quicker alternative would need to be developed, or the current load/unload time for this process reduced in order for this combination to be applicable. These high-end wood products would also be unlikely to feature a large production quantity, minimizing the importance of material handling efficiency.

5.3.8. Manufacturing Scenario 8

The factor levels for this scenario can be found in Table 17 and the statistics can be found in *Table 18*.

Table 17: Scenario 8 Factor Levels

Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**
-1	-1	-1	-1

Table 18: Scenario 8 Statistics

Part Geometry	Average Response Values			
	Rank Correlation	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
Bearing Block	0.24	-0.03	473.99%	481.03%
Square Support	0.28	0.22	510.02%	506.00%

Like with the above treatment combination, this combination features similar statistics across both tested parts. The values for the correlation responses are also extremely low for both parts (the lowest values recorded, in fact), making a categorization of the part within the first category reasonable. Considering the layout during process plan generation is critical, and failing to do so could lead to a significant error in selecting the configuration to manufacture.

The afore-mentioned manufacturing scenarios with moderately-sized metal parts, like staplers and some automotive parts, probably fits best within this combination. That scenario is likely to feature low labor costs and low material costs. However, unlike the sixth treatment combination, this treatment combination features low load/unload times. These low load/unload times are likely to be a characteristic of the afore-mentioned industry as many of the goods are mass produced and do not require intricate machining. Because of this, this treatment combination is probably the best fit for that manufacturing scenario.

The manufacture of low to medium-end moderately-sized wood products could also be captured by this scenario. In that situation the labor rates would be on the low-end, unlike the scenario mentioned in the seventh treatment combination. However, as mentioned with the seventh treatment combination, this manufacturing scenario is best modeled with a high load/unload time because of the likely use of wood glue. Thus, the sixth treatment combination is likely to capture this situation better, unless an alternative process is developed or load/unload times for wood glue are reduced.

6. Conclusions

In this research, the impact of the facility layout is overstated because the material handling cost model includes non-layout dependent factors (e.g. warehouse worker labor rate). However, the material handling cost model also only accounts for loaded material handling movement. This failure to include empty vehicle travel understates the impact of the layout. In worst case scenarios, the material handling distance could be doubled with the inclusion of empty vehicle travel. These two assumptions may balance each other out, but it is difficult to assess their magnitude. A more accurate material handling cost model should probably account for both these factors to improve its precision.

Some noteworthy conclusions were drawn from this research. First, the important factors related to the impact of utilizing an arbitrary layout during process plan generation were discovered. These factors have an order of importance that is restated below:

1. Part Volume
2. Load/Unload Time

3-tie. Material Cost
3-tie. Labor Rate

From the analysis of the treatment combinations, it is clear that the part volume factor is by far the most important factor. A high-end part volume factor makes the assumption of an arbitrary layout perfectly acceptable, whereas a low-end value means that it is likely the layout needs to be considered during process plan generation. This relationship does assume that there is a positive relationship between manufacturing cost and part volume. This is a reasonable assumption for most industries, but there are exceptions, like micromanufacturing, where this assumption is invalid. The load/unload time factor is the second most important factor, with the low-end value influencing the assumption of an arbitrary layout in such a way that the layout is more likely to need consideration during process plan generation. Conversely, the high-end value influences manufacturing scenarios in such a way as to make it less likely that layout optimization is needed. The material cost factor is one of the less important factors, but still important to consider. It has a dual effect, with the high-end value making high join configurations more cost-effective, which in turn increases the importance of material handling efficiency because there are now more material handling moves required. On the other hand, a low-end value decreases the total manufacturing cost for that scenario making the material handling cost compose a larger portion of the total manufacturing cost. Finally, the labor rate factor is tied with material cost as one of the less important factors, but still warrants consideration. A high-end value makes the consideration of the layout during process plan generation less necessary, because it increases the total manufacturing cost of the part making material handling compose a smaller portion of the cost. On the other hand, a low-end value has the opposite effect, making it more likely the layout will need to be considered during process plan generation.

Next the tested treatment combinations for these four factors were categorized into three different subsets. A brief overview of what these categories are is listed below:

1. Situations where it is critical that the layout be accounted for in process plan generation because the assumption of an arbitrary layout is completely unreasonable.

2. Situations where considering the layout during process plan generation is important for optimality, but the assumption of an arbitrary layout is unlikely to lead to significant amounts of error.
3. Situations where the layout assumption is reasonable, and the layout does not need to be considered in process plan generation.

As mentioned above the part volume factor is the most important factor. Because of the effect that it has on this research, there are no treatment combinations where the part volume is at its high-end value and it is necessary or warranted to consider the layout during process plan generation. Thus, the eight other treatment combinations where the part volume factor was at its low-end value were considered in-depth. An overview of these combinations and how they were categorized is shown in Table 19:

Table 19: Treatment Combination Summary

Treatment Combination Number	**Factor Levels**				**Layout Consideration Category**
	Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**	
1	-1	1	1	1	2
2	-1	1	1	-1	2
3	-1	1	-1	1	2
4	-1	1	-1	-1	2
5	-1	-1	1	1	3
6	-1	-1	1	-1	1
7	-1	-1	-1	1	1
8	-1	-1	-1	-1	1

Based on the analysis, seven of the eight treatment combinations that featured a low-end part volume warrant some type of layout consideration during process plan generation. For three of these combinations it is critical that the layout be considered, while for the other combinations is important that the layout be considered if optimality is desired. Further explanation for the reasoning behind the categorization for each of these combinations can be found above in the results section.

Several real-world manufacturing scenarios were also evaluated in order to determine their relation to the treatment combinations mentioned above. When considering these scenarios, the production volume for any such scenario was also considered. The importance of material handling efficiency for a particular scenario depends on the production quantity for that particular scenario. The higher the production quantity, the more important material handling efficiency is to the bottom line. It is also important to note that if a particular manufacturing scenario is not using any sort of joining processes, then this research is not applicable to that specific situation. A summary of the manufacturing scenarios that were analogized for each treatment combination is shown in

Table 20. If the production volume for a scenario is unlikely to be large, then that is also noted within the table. More details on the specific scenarios can be found above in the results section.

Table 20: Table of Real-World Manufacturing Scenarios

Treatment Combination Number	Analogous Manufacturing Scenarios
1	Moderately-sized defense parts
	Moderately-sized high-end luxury goods (production volume is unlikely to be large)
	Moderately-sized aerospace parts (production volume is unlikely to be large)
2	Moderately-sized defense parts
	Moderately-sized aerospace parts (production volume is unlikely to be large)
	Moderately-sized computer electronics parts
3	Similar scenarios as combinations one and two; these scenarios are likely better encapsulated by either of those combinations
4	Moderately-sized high-end luxury goods (production volume is unlikely to be large)
	Similar scenarios as combinations one and two; these scenarios are likely better encapsulated by either of those combinations
5	N/A
6	Low to medium-end wood manufacturing of moderately-sized parts
	Moderately-sized metal goods made from cheaper metals
7	High-end wood manufacturing of moderately-sized parts (production volume is unlikely to be large)
	Similar scenarios as combinations six and eight; these scenarios are likely better encapsulated by either of those combinations
8	Low to medium-end wood manufacturing of moderately-sized parts
	Moderately-sized metal goods made from cheaper metals

The most important scenarios are likely to be low to medium-end wood manufacturing, the manufacture of moderately sized goods made from cheaper metals, and the computer electronics industry.

This research raises questions that could be answered in further research. First, the finite capacity issue could be considered. This problem arises from the fact that a certain roster of machines may be unable to manufacture the production volume necessary to meet customer demand, have unsatisfactory defect numbers, or have a longer processing time than newer machines on the market. From this portfolio of machines, it could then be considered when it would be profitable to redo the facility layout and purchase new machines to solve any of the above issues. The layout optimization problem within process plan generation could also be considered. This research has shown for what types of situations, the assumption of an arbitrary layout is likely to lead to error during process plan generation. Further research could consider how to incorporate a method of layout optimization within process plan generation for the situations discussed above, where the assumption of an arbitrary layout is likely to lead to error in selecting a configuration to manufacture.

Appendices

Appendix A Methodology Appendices

Appendix A.1. Cutting Plane Search Method

In order to determine suitable joining locations, a search method is required to find effective cutting planes. This is a topic that has been explored in literature, as there are multiple different search methods. For this project, a method called area decomposition will be used, a technique that is described by Massoni and Campbell (2017b). This method selects cutting planes based on the change in cross-sectional areas along a given axis (Massoni & Campbell, 2017b). The method looks for large changes in area, because such changes show that there may be the possibility of significant waste reduction in that area (Massoni & Campbell, 2017b). By placing a cutting plane at the location where a larger cross-sectional area changes to a smaller area, a significant amount of waste may be saved (Massoni & Campbell, 2017b).

Area decomposition searches along 13 different directions, in which it considers the resulting changes in cross-sectional area (Massoni & Campbell, 2017b). The three basic orthogonal directions, in relation to the part, make up three of the 13 directions (Massoni & Campbell, 2017b). In order to find the other 10 directions, the area of every face on the part with an identical normal is summed (Massoni & Campbell, 2017b). Then the top 10 directions with areas above a cutoff threshold are chosen as the 10 remaining directions to search along (Massoni & Campbell, 2017b). The search method then analyzes cutting planes in each of the 13 directions (Massoni & Campbell, 2017b). The method then selects the 10 largest changes in area for each direction that have a change greater than 1% (Massoni & Campbell, 2017b). These selections form the cutting planes that will be considered for possible joins (Massoni &

Campbell, 2017b). The planes are then run through a preliminary cost model to cull the number of planes considered for the manufacturing plan search to a reasonable number (Massoni & Campbell, 2017b).

Appendix A.2. Eliminating Identical Results

While Katana is effective in generating a variety of different assembly combinations for each part, sometimes the program can generate two or more configurations that are nearly identical. This will result in redundancy when analyzing the results of this research. Thus, it is necessary to define some criteria that can be used to eliminate identical configurations within a single part's results. These criteria are defined below:

- Two or more configurations feature the same number of cutting planes that are in nearly identical locations. Although these cutting planes are not exactly identical, the slight variation in where they are located does not allow any significant features to be joined in ways that are not feasible in the other configuration. An illustration of this concept is shown in Figure 11.

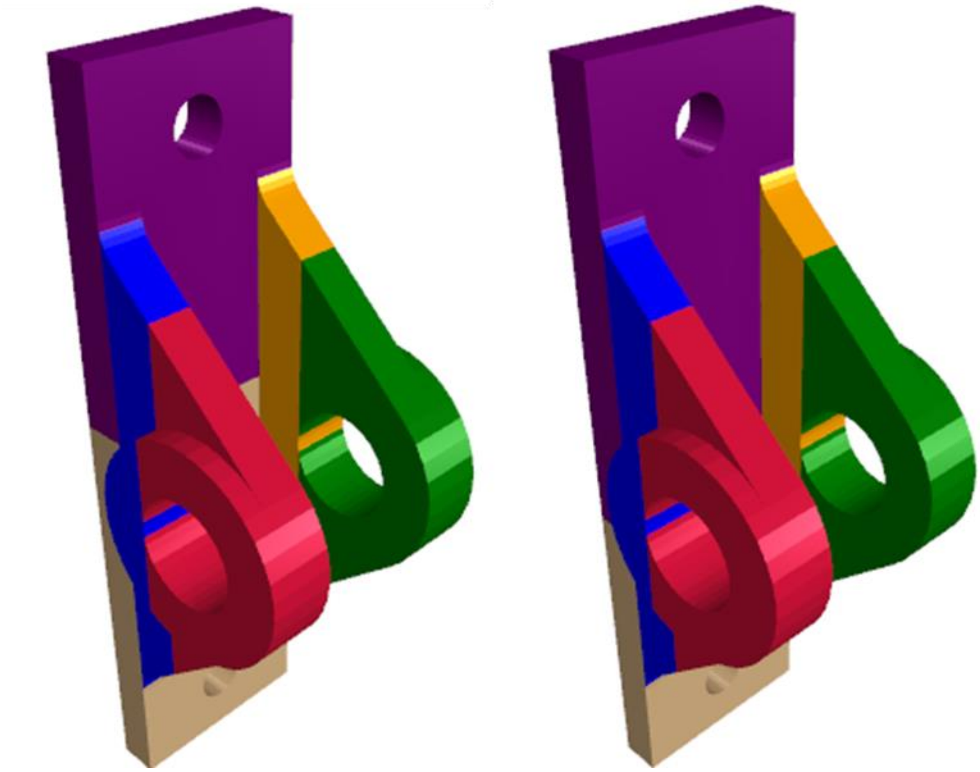


Figure 11: Slight variation in cutting plane location

- Two or more configurations feature an identical number of cutting planes, with the only difference between the configurations being that one symmetrical feature is chosen in a certain configuration while the other configurations select one of the other versions of the symmetrical feature. An illustration of this is shown below in Figure 12.

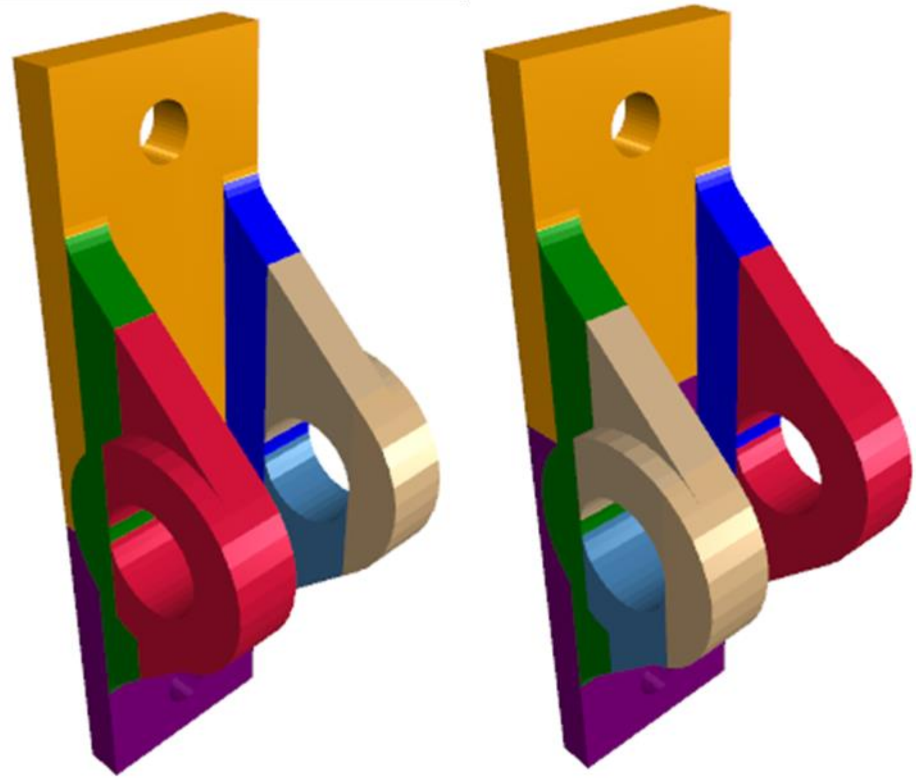


Figure 12: Symmetrical Configurations

Appendix A.3. Cross-Sectional Joining Area

There is a practical limit on the size of parts that can be joined together. If the parts are too large, they simply will not fit in the machine that does the joining process. If a theoretical part is large enough that cross-sectional joining area becomes a constraint, then the issue of assuming arbitrary layout for the purpose of determining the best configuration becomes moot. A part that is above maximum cross-sectional area for available joining processes can no longer be joined using those processes. This limitation constrains the part so that it can only be manufactured in one way; the part must now be machined out of a single blank. When the part can only be manufactured in a single way, there is no longer a decision to be made in how to manufacture that part. Thus, the assumption of an arbitrary layout would be a perfectly acceptable assumption for situations in which the maximum cross-sectional joining area is a constraint.

Linear friction welding is one such popular joining method that has a practical limit on its weld area. Thompson currently manufactures a machine with a maximum weld area of 20 in^2 ("Machines," n.d.). This is currently the maximum practical limit for this type of joining process. For other joining methods, joining area is not a significant practical limit. For example, processes like wood gluing and rotary friction welding are not as constrained by a practical limit. Future technological developments may also increase maximum weld areas for other processes like linear friction welding so that is no longer a practical concern. Thus, the theoretical limit may be best be modeled with an uncapped value. This theoretical, uncapped value will be used for the purposes of this research. To model this in the Katana software, the value will be set arbitrarily high (e.g. 900000 in^2).

Appendix B Low-Level Material-handling Cost

Appendix B.1. Layout

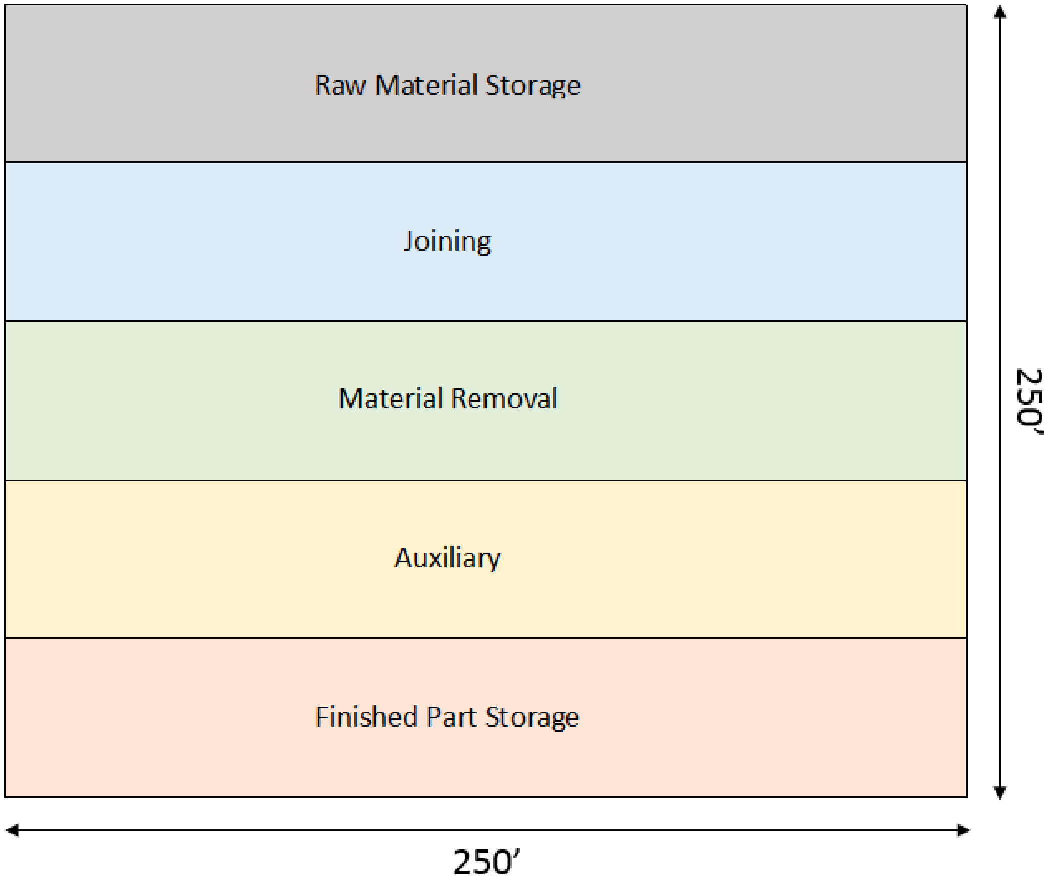


Figure 13: Low-level Layout

Appendix B.2. Department Centroids

Department Name	Centroid
Raw Material Storage	(125, 225)
Joining	(125, 175)
Material Removal	(125, 125)
Auxiliary	(125,75)
Finished Part Storage	(125, 25)

Appendix B.3. Rectilinear Interdepartmental Distances From/To Chart

From/To (All units in feet)	Raw Material Storage	Joining	Material Removal	Auxiliary	Finished Part Storage
Raw Material Storage	X	X	X	X	X
Joining	50	X	X	X	X
Material Removal	100	50	X	X	X
Auxiliary	150	100	50	X	X
Finished Part Storage	200	150	100	50	X

Average Interdepartmental Distance = 100 Feet

Appendix B.4. Cost Per Move Calculation

Cost per move calculated using Equation 1.

Inputs (units have been changed so they are consistent):

- *Labor Rate*: $15/hour
- *LoadUnloadTime*: 0.0833 hours
- *Speed*: 9,828 feet per hour
- *# of Operators*: 1
- *Distance*: 100 feet

$$Cost\ Per\ Move = \left(0.0833\ hours + \frac{100\ feet}{9{,}828\ feet\ per\ hour}\right) \times \left(1 \times \frac{\$15}{hour}\right)$$

Cost per Move = $1.402125

Appendix C High-level Material Handling Cost

Appendix C.1. Layout

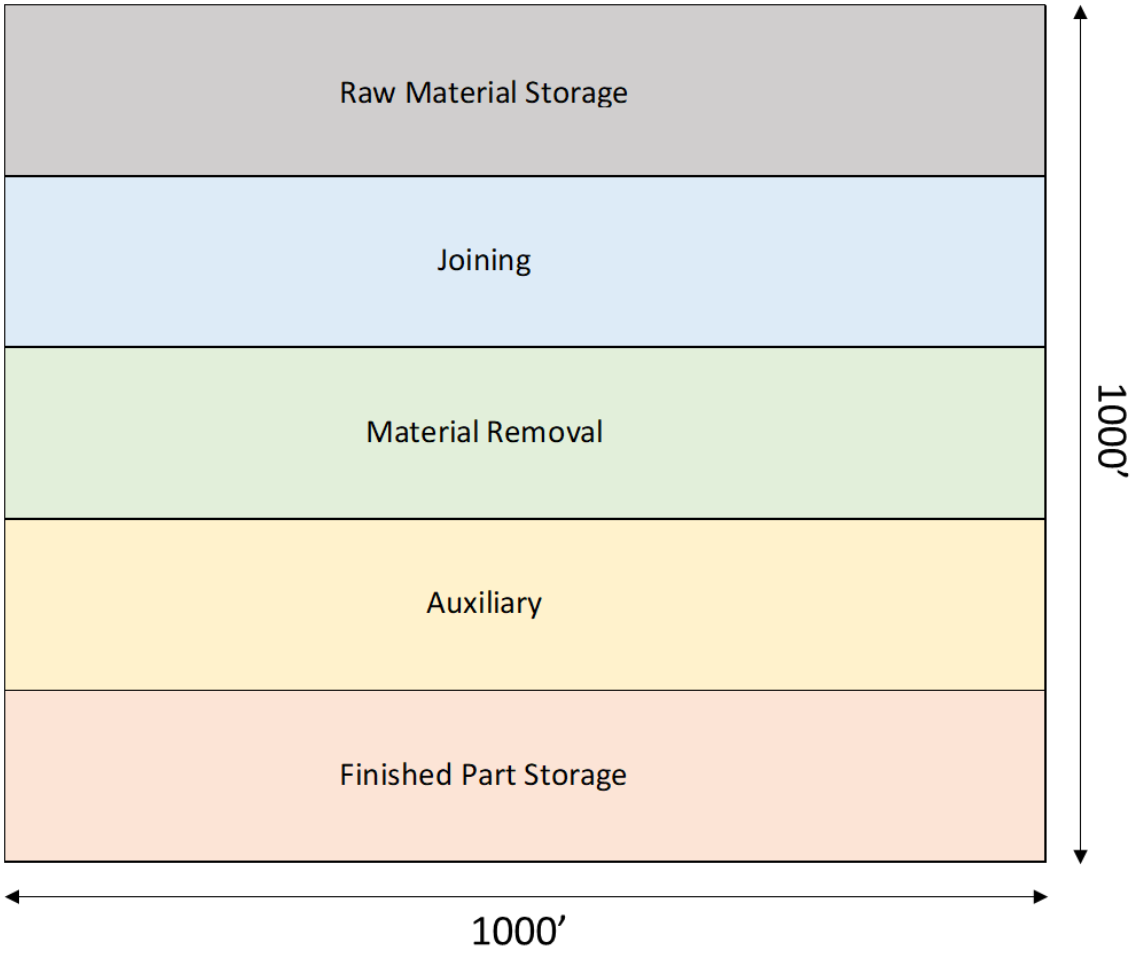


Figure 14: High-level Layout

Appendix C.2. Department Centroids

Department Name	Centroid
Raw Material Storage	(500, 900)
Joining	(500, 700)
Material Removal	(500, 500)
Auxiliary	(500, 300)
Finished Part Storage	(500, 100)

Appendix C.3. Rectilinear Interdepartmental Distances From/To Chart

From/To (All units in feet)	Raw Material Storage	Joining	Material Removal	Auxiliary	Finished Part Storage
Raw Material Storage	X	X	X	X	X
Joining	200	X	X	X	X
Material Removal	400	200	X	X	X
Auxiliary	600	400	200	X	X
Finished Part Storage	800	600	400	200	X

Average Rectilinear Interdepartmental Distance = 400 feet

Appendix C.4. Cost Per Move Calculation

Cost per move calculated using Equation 1.

Inputs (units have been changed so they are consistent):
- *Labor Rate*: $27/hour
- *LoadUnloadTime*: 0.25 hours
- *Speed*: 900 feet per hour
- *# of Operators*: 2
- *Distance*: 400 feet

$$Cost\ Per\ Move = \left(0.25\ hours + \frac{400\ feet}{900\ feet\ per\ hour}\right) \times \left(2 \times \frac{\$27}{hour}\right)$$

Cost per Move = $37.50

Appendix D Factor Levels

Table 21: Factor Levels

Factor Name	High-End Value	Low-End Value
Material Cost	\$26.00/lb. (Density: 0.16 lb/in^3)	\$0.40/lb. (Density: 0.28 lb/in^3)
Material Removal Rate	100 in^3/min	1 in^3/min
Part Volume	216,000 in^3	148 in^3
Possible Blank Types	Rectangular Bar Stock, Circular Bar Stock, and Waterjet Plate	Rectangular Bar Stock and Circular Bar Stock
Load/Unload Time	60 minutes	5 minutes
Joining rate	5 in^2/second	0.01 in^2/second
Labor Rate	\$44.00/hour	\$10.00/hour

Parts to be Tested

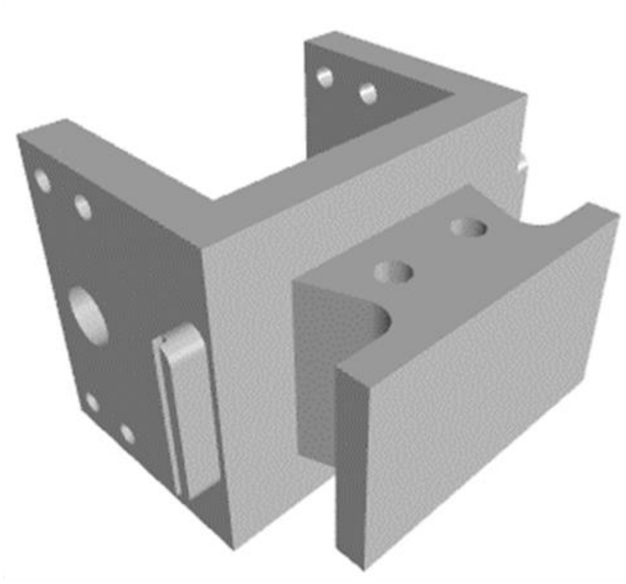


Figure 15: The "Square Support" part

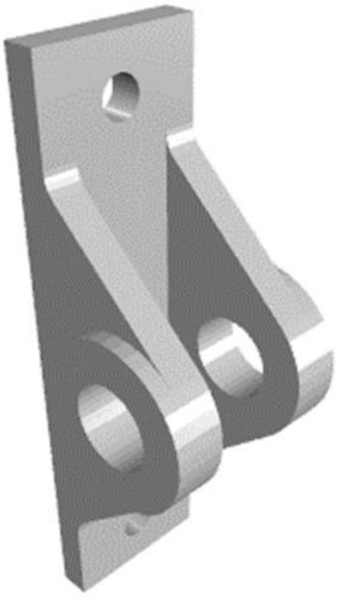


Figure 16: The "Bearing Block" part

Appendix E Treatment Combinations

	Factor Levels						
Factor Letters	A	B	C	D	E	F	G
Run	**Material Cost**	**Material Removal Rate**	**Part Volume**	**Possible Blank Types**	**Load/Unload Time**	**Joining rate**	**Labor Rate**
1	-1	-1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	-1
4	1	1	-1	-1	-1	1	1
5	-1	-1	1	-1	-1	-1	1
6	1	-1	1	-1	-1	1	-1
7	-1	1	1	-1	-1	1	-1
8	1	1	1	-1	-1	-1	1
9	-1	-1	-1	1	-1	-1	-1
10	1	-1	-1	1	-1	1	1
11	-1	1	-1	1	-1	1	1
12	1	1	-1	1	-1	-1	-1
13	-1	-1	1	1	-1	1	-1
14	1	-1	1	1	-1	-1	1
15	-1	1	1	1	-1	-1	1
16	1	1	1	1	-1	1	-1
17	-1	-1	-1	-1	1	1	-1
18	1	-1	-1	-1	1	-1	1
19	-1	1	-1	-1	1	-1	1
20	1	1	-1	-1	1	1	-1
21	-1	-1	1	-1	1	-1	-1
22	1	-1	1	-1	1	1	1
23	-1	1	1	-1	1	1	1
24	1	1	1	-1	1	-1	-1
25	-1	-1	-1	1	1	-1	1
26	1	-1	-1	1	1	1	-1
27	-1	1	-1	1	1	1	-1
28	1	1	-1	1	1	-1	1
29	-1	-1	1	1	1	1	1
30	1	-1	1	1	1	-1	-1
31	-1	1	1	1	1	-1	-1
32	1	1	1	1	1	1	1

Appendix F Numerical Response Example with Bearing Block Part

Appendix F.1. Factor Levels

Material Cost	Material Removal Rate	Part Volume	Possible Blank Types	Load/Unload Time	Joining Rate	Labor Rate
1	-1	-1	-1	-1	-1	-1

Appendix F.2. Computation of High-Level and Low-Level Material Handling Scenarios

Original Rank	Original Cost	# of MH Moves	With High-Level Material Handling Cost	With Low-Level Material Handling Cost
1	$830.70	13	$1,318.20	$848.93
2	$864.18	11	$1,276.68	$879.60
3	$897.65	9	$1,235.15	$910.27
4	$898.05	9	$1,235.55	$910.67
5	$904.11	9	$1,241.61	$916.73
6	$944.08	7	$1,206.58	$953.89
7	$953.55	7	$1,216.05	$963.36
8	$981.84	8	$1,281.84	$993.06
9	$1,052.13	5	$1,239.63	$1,059.14
10	$1,255.20	5	$1,442.70	$1,262.21

Appendix F.3. Computation of Rank Correlation Response

High-Level Rank	**Low-Level Rank**
9	1
7	2
3	3
4	4
6	5
1	6
2	7
8	8
5	9
10	10

Correlation = 0.054545455

Appendix F.4. Computation of Percentile Correlation Response

High-Level Percentile	**Low-Level Percentile**
47.27%	0.00%
29.69%	7.42%
12.10%	0.148424929
0.122691852	14.94%
14.84%	16.41%
0.00%	25.40%
4.01%	27.69%
31.87%	34.87%
14.00%	50.86%
100.00%	100.00%

Correlation = 0.654972275

Appendix F.5. Computation of Percent Change Responses

% Change for Selected Configuration
55.28%
45.14%
35.69%
35.67%
35.44%
26.49%
26.23%
29.08%
17.04%
14.30%

Average Percent Change = 32.04%
Optimal Configuration Percent Change = 55.28%

Appendix G Assumptions

This research makes a number of assumptions:

- Costs are only looked at on single-use basis. This means that items such as interest rates, wear and tear causing depreciation, and amortized costs will not be included. The only non-single-use cost that will be included will be included is cutting tool depreciation, as these tools wear much more quickly than other pieces of equipment.
- The facility layout for a particular manufacturing scenario must be large, and material handling must range somewhere between moderate to expensive in cost. If these assumptions are not met, then it is highly unlikely that material handling efficiency will be important to the bottom line for that particular scenario.
- Single-piece flow is assumed for material handling moves between processes. One part is moved at a time from department to department. Batch processing is also not considered. Each part is assumed to be processed at each step, one at a time. Within Katana, many of the cost models are designed for single-piece flow. Batch processing is not considered so that it is consistent with the assumption of single-piece flow in the model.
- Overhead costs are not included in the model. Things that would normally be included within overhead costs include: manager salaries, utility costs (e.g. water and electricity), the rent of the assumed manufacturing facility, etc. This is done because this research is focused on the operational cost of material movement.
- All blanks are assumed to have the same base cost per unit pound. Normally, certain types of blanks would cost more than other types. For example, a waterjet plate blank

would normally cost more than a rectangular plate blank. This research could connect to a variety of different industries. The cost for different blank types will vary from situation to situation, so they are assumed to have the same base cost in this research to maintain consistency.

- Auxiliary processes are assumed to always have a duration of one hour, independent of any factor tested in this research. The only cost for that hour is the applicable labor rate, based on that factor level. These types of processes are treated as a fixed cost in the research.
- Capacity issues are not considered. A machine can always be used when it is required by the process plan.
- All factors have a positive, linear effect on cost. There are no outliers in this relationship (e.g. micromanufacturing would be an outlier for the part volume factor).
- Some type of joining process is available for the manufacturing scenarios considered in this research.
- Weight and volume are not considered when determining if any specific type of process or material handling method is viable for a specific part. The functionality for this consideration was not considered because part volume is a factor within the designed experiment.
- Empty material handling travel is not accounted for. A more accurate material handling cost model should probably account for empty travel in some form.

Appendix H Table of Responses and Normal Probability Plots

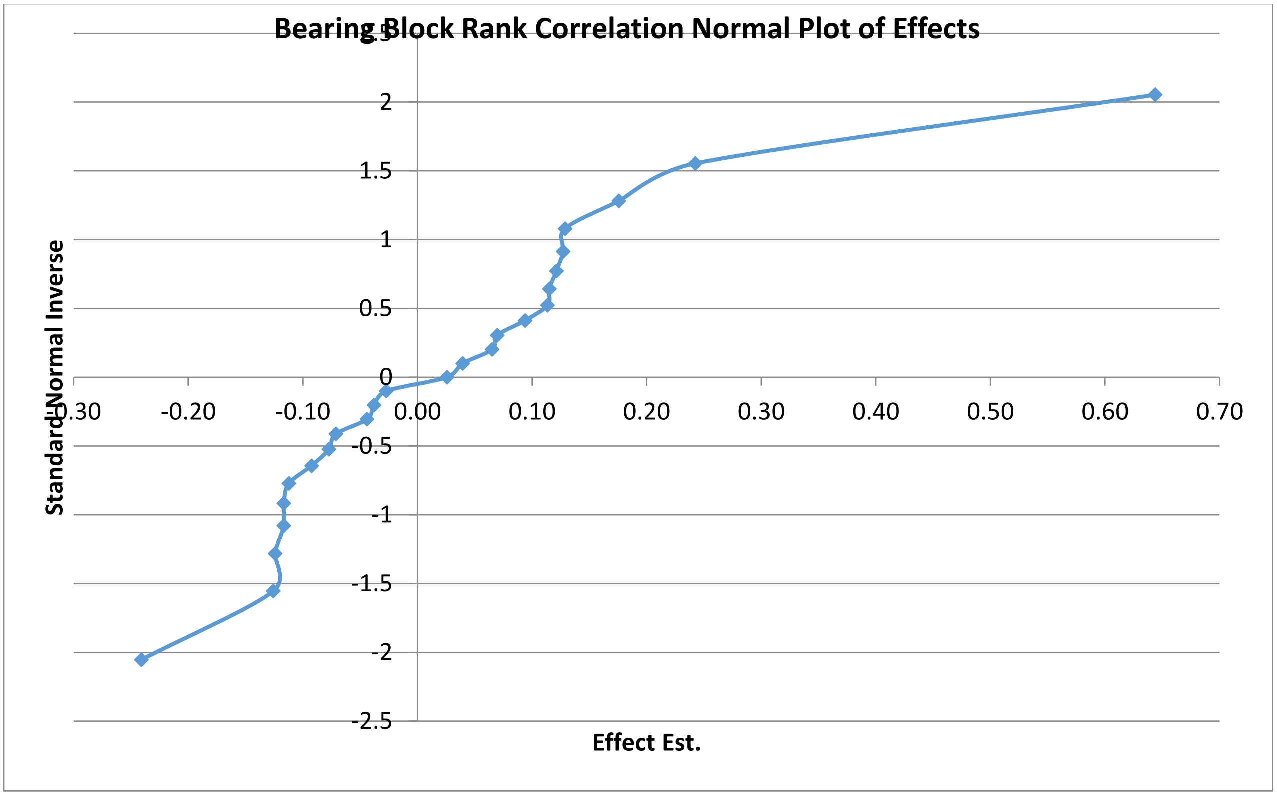
Appendix H.1. Bearing Block Responses

Run	Rank Correlation	Percentile Correlation	Average Percent Change	Optimal Configuration Percent Change
1	-0.684848485	-0.499959623	188.65%	310.00%
2	0.054545455	0.654972275	32.04%	55.28%
3	0.478787879	0.211185824	471.22%	562.57%
4	-0.006060606	0.615098633	31.41%	53.53%
5	0.987878788	0.999989649	0.30%	0.53%
6	1	0.999999934	0.02%	0.04%
7	1	0.99990129	0.84%	1.58%
8	1	0.999999719	0.03%	0.04%
9	0.006060606	-0.276152617	476.77%	399.48%
10	0.115151515	0.83680068	39.83%	49.67%
11	0.818181818	0.87933029	323.65%	239.60%
12	0.115151515	0.767850556	42.77%	52.88%
13	1	0.999983851	0.57%	1.11%
14	1	0.999999798	0.02%	0.04%
15	0.987878788	0.999847247	0.68%	1.08%
16	1	0.999999928	0.02%	0.04%
17	0.927272727	0.918641287	298.57%	216.10%
18	0.309090909	0.032998618	26.64%	20.99%
19	1	0.999813682	103.33%	0.00%
20	-0.151515152	0.559275818	31.68%	53.32%
21	1	0.999924939	0.62%	1.06%
22	1	0.999999948	0.02%	0.04%
23	0.987878788	0.999615007	0.92%	1.55%
24	1	0.999999727	0.03%	0.04%
25	0.672727273	0.647814352	91.44%	90.88%
26	0.503030303	0.770462511	40.97%	50.80%
27	0.563636364	0.59066643	344.87%	335.29%
28	0.939393939	0.756170837	31.33%	22.88%
29	1	0.999998251	0.27%	0.55%
30	1	0.99999975	0.03%	0.04%
31	1	0.999923134	0.79%	1.29%
32	1	0.999999985	0.02%	0.04%

Appendix H.2. Bearing Block Normal Probability Plots

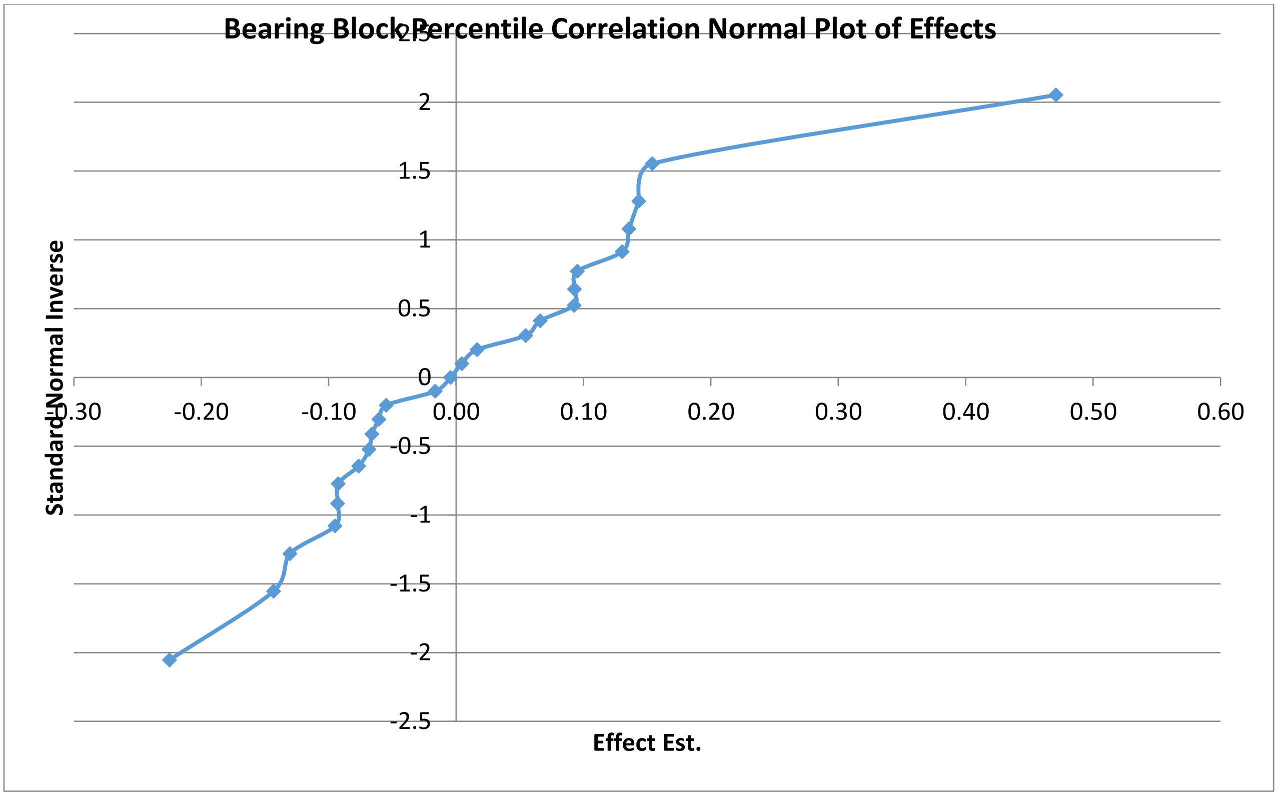
Rank Correlation

Factor	Sorted Effects	Standard Normal Inverse
CE	-0.24	-2.053748911
AB	-0.13	-1.554773595
BE	-0.12	-1.281551566
A	-0.12	-1.080319341
BC	-0.12	-0.915365088
CD	-0.11	-0.772193214
F	-0.09	-0.643345405
AE	-0.08	-0.524400513
BF	-0.07	-0.412463129
CG	-0.04	-0.305480788
DE	-0.04	-0.201893479
AF	-0.03	-0.100433721
BD	0.03	0
G	0.04	0.100433721
AG	0.07	0.201893479
AD	0.07	0.305480788
CF	0.09	0.412463129
D	0.11	0.524400513
B	0.12	0.643345405
AC	0.12	0.772193214
DF	0.13	0.915365088
DG	0.13	1.080319341
BG	0.18	1.281551566
E	0.24	1.554773595
C	0.64	2.053748911


Bearing Block Rank Correlation Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70

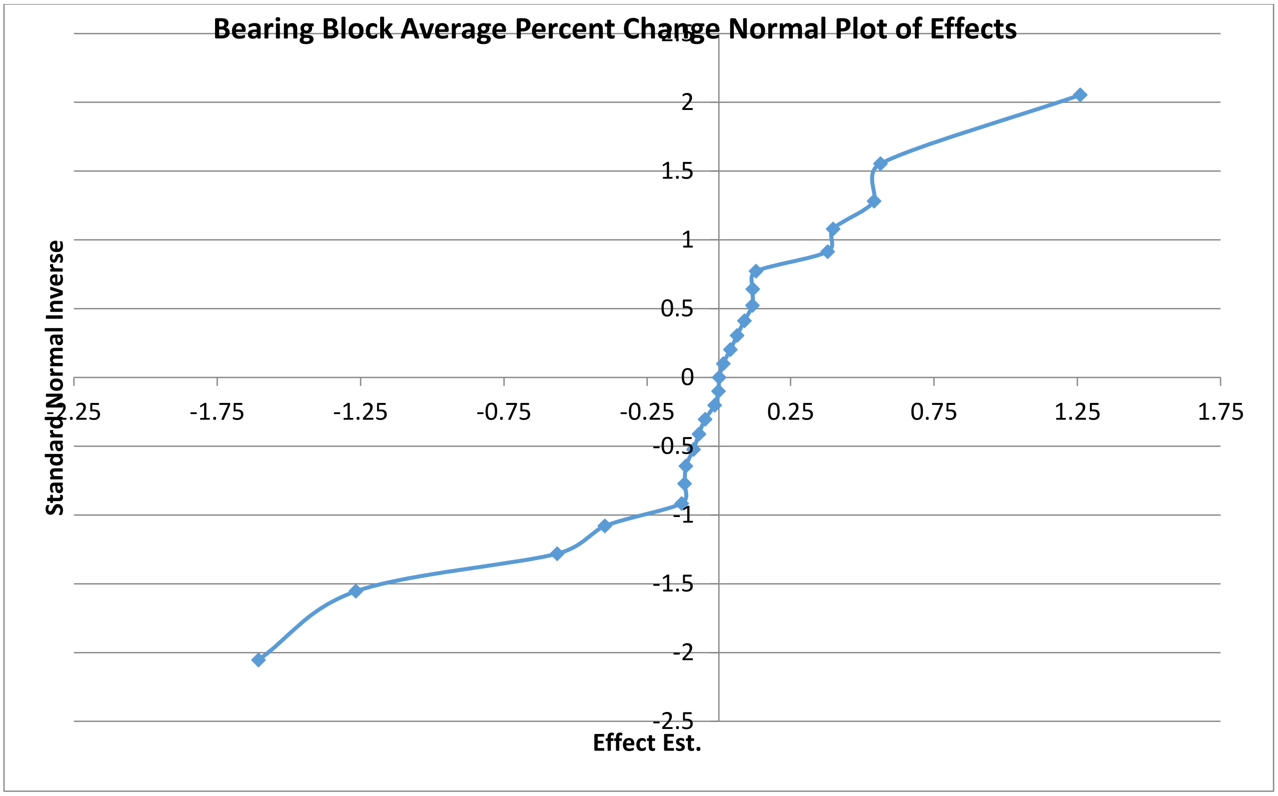
Percentile Correlation

Factor	Sorted Effects	Standard Normal Inverse
AE	-0.22	-2.053748911
BC	-0.14	-1.554773595
CE	-0.13	-1.281551566
AC	-0.10	-1.080319341
AB	-0.09	-0.915365088
CD	-0.09	-0.772193214
BE	-0.08	-0.643345405
AG	-0.07	-0.524400513
BF	-0.07	-0.412463129
DE	-0.06	-0.305480788
CF	-0.05	-0.201893479
BD	-0.02	-0.100433721
CG	0.00	0
G	0.00	0.100433721
AF	0.02	0.201893479
F	0.05	0.305480788
AD	0.07	0.412463129
D	0.09	0.524400513
DF	0.09	0.643345405
A	0.10	0.772193214
E	0.13	0.915365088
BG	0.14	1.080319341
B	0.14	1.281551566
DG	0.15	1.554773595
C	0.47	2.053748911


Bearing Block Percentile Correlation Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60

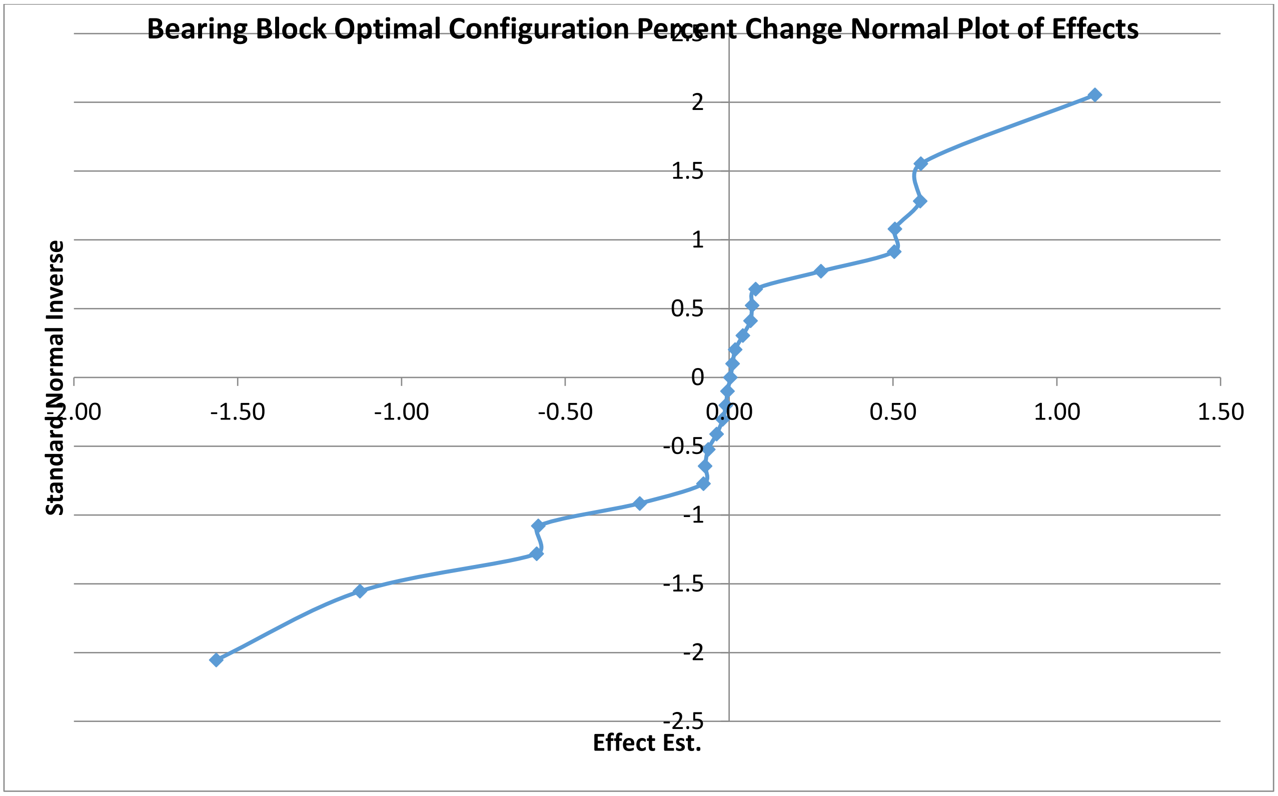
Average Percent Change

Factor	Sorted Effects	Standard Normal Inverse
C	-1.61	-2.053748911
A	-1.27	-1.554773595
G	-0.56	-1.281551566
E	-0.40	-1.080319341
CD	-0.13	-0.915365088
AB	-0.12	-0.772193214
BC	-0.11	-0.643345405
AD	-0.09	-0.524400513
DE	-0.07	-0.412463129
BE	-0.05	-0.305480788
CF	-0.01	-0.201893479
AF	0.00	-0.100433721
BD	0.00	0
F	0.02	0.100433721
DG	0.04	0.201893479
BG	0.06	0.305480788
BF	0.09	0.412463129
B	0.12	0.524400513
DF	0.12	0.643345405
D	0.13	0.772193214
AE	0.38	0.915365088
CE	0.40	1.080319341
AG	0.54	1.281551566
CG	0.56	1.554773595
AC	1.26	2.053748911


Bearing Block Average Percent Change Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2.25
-1.75
-1.25
-0.75
-0.25
0.25
0.75
1.25
1.75

Optimal Configuration Percent Change

Factor	Sorted Effects	Standard Normal Inverse
C	-1.57	-2.053748911
A	-1.13	-1.554773595
G	-0.59	-1.281551566
E	-0.58	-1.080319341
BG	-0.27	-0.915365088
BC	-0.08	-0.772193214
AB	-0.07	-0.643345405
CF	-0.06	-0.524400513
BE	-0.04	-0.412463129
D	-0.02	-0.305480788
BF	-0.01	-0.201893479
BD	-0.01	-0.100433721
AF	0.00	0
AD	0.01	0.100433721
CD	0.02	0.201893479
DG	0.04	0.305480788
F	0.07	0.412463129
DF	0.07	0.524400513
B	0.08	0.643345405
DE	0.28	0.772193214
AE	0.50	0.915365088
AG	0.51	1.080319341
CE	0.58	1.281551566
CG	0.59	1.554773595
AC	1.12	2.053748911


Bearing Block Optimal Configuration Percent Change Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50

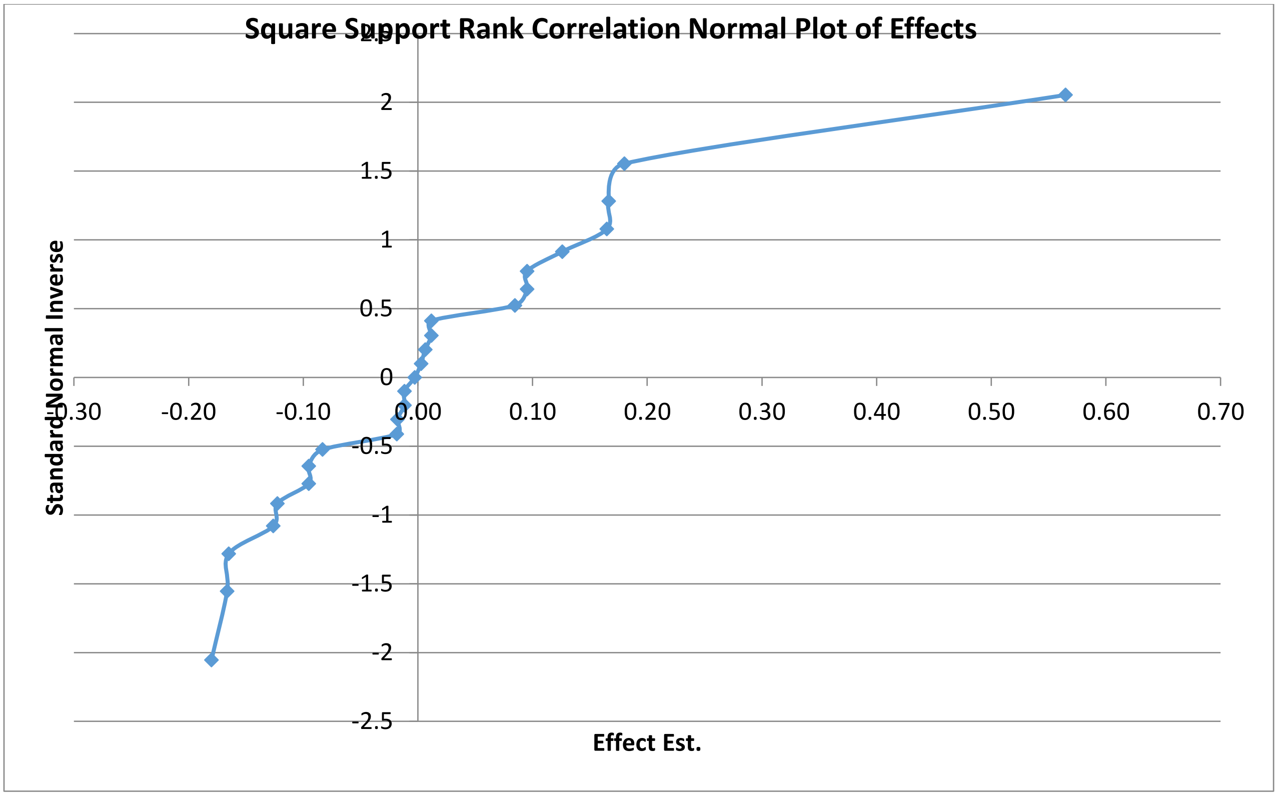
Appendix H.3. Square Support Responses

Run	Rank Correlation	Percentile Correlation	Average Percent Change	Optimal Configuration Percent Change
1	-0.127272727	-0.295870466	271.42%	300.01%
2	0.090909091	0.915556311	44.60%	69.81%
3	1	0.991623365	578.84%	500.02%
4	0.090909091	0.906406103	42.86%	66.44%
5	1	0.999999903	0.38%	1.00%
6	1	0.999999996	0.02%	0.05%
7	1	0.999994857	0.84%	1.79%
8	1	0.999999996	0.02%	0.05%
9	-0.45	-0.559618562	441.20%	511.98%
10	0.357575758	0.615932374	47.16%	58.44%
11	0.636363636	0.69898213	342.24%	311.48%
12	0.563636364	0.92954749	44.72%	73.87%
13	1	0.99999915	0.68%	1.62%
14	1	0.999999997	0.02%	0.05%
15	1	0.999992018	0.68%	1.35%
16	1	0.999999996	0.02%	0.05%
17	0.248484848	0.224107138	322.13%	342.04%
18	0.866666667	0.944532566	28.60%	27.10%
19	1	0.999913295	107.36%	77.56%
20	0.406060606	0.896118229	43.13%	66.08%
21	1	0.999999117	0.65%	1.52%
22	1	0.999999997	0.02%	0.05%
23	1	0.999995282	0.82%	1.77%
24	1	0.999999996	0.02%	0.05%
25	0.636363636	0.354928894	76.68%	101.08%
26	0.418181818	0.495576204	48.25%	38.79%
27	0.442424242	0.406661201	312.30%	288.64%
28	0.781818182	0.596725351	36.30%	30.77%
29	1	0.999999908	0.44%	1.21%
30	1	0.999999996	0.02%	0.05%
31	1	0.999994352	0.79%	1.67%
32	1	0.999999996	0.02%	0.05%

Appendix H.4. Square Support Normal Probability Plots

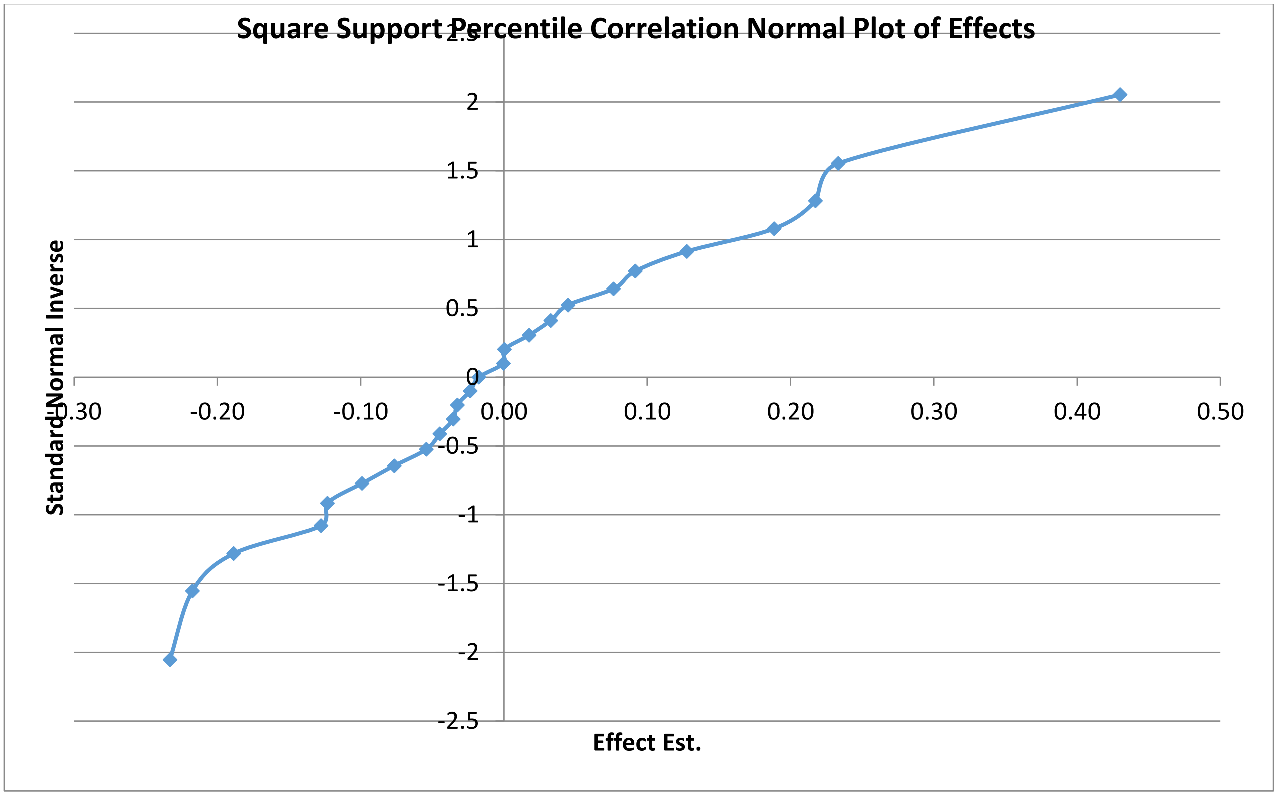
Rank Correlation

Factor	Sorted Effects	Standard Normal Inverse
BC	-0.18	-2.053748911
AB	-0.17	-1.554773595
CE	-0.16	-1.281551566
F	-0.13	-1.080319341
BE	-0.12	-0.915365088
BF	-0.10	-0.772193214
CG	-0.10	-0.643345405
BG	-0.08	-0.524400513
DE	-0.02	-0.412463129
AG	-0.02	-0.305480788
AC	-0.01	-0.201893479
D	-0.01	-0.100433721
AF	0.00	0
BD	0.00	0.100433721
AE	0.01	0.201893479
A	0.01	0.305480788
CD	0.01	0.412463129
DG	0.08	0.524400513
G	0.10	0.643345405
AD	0.10	0.772193214
CF	0.13	0.915365088
E	0.16	1.080319341
DF	0.17	1.281551566
B	0.18	1.554773595
C	0.56	2.053748911


Square Support Rank Correlation Normal Plot of Effects
Standard Normal Inverse
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
Effect Est.

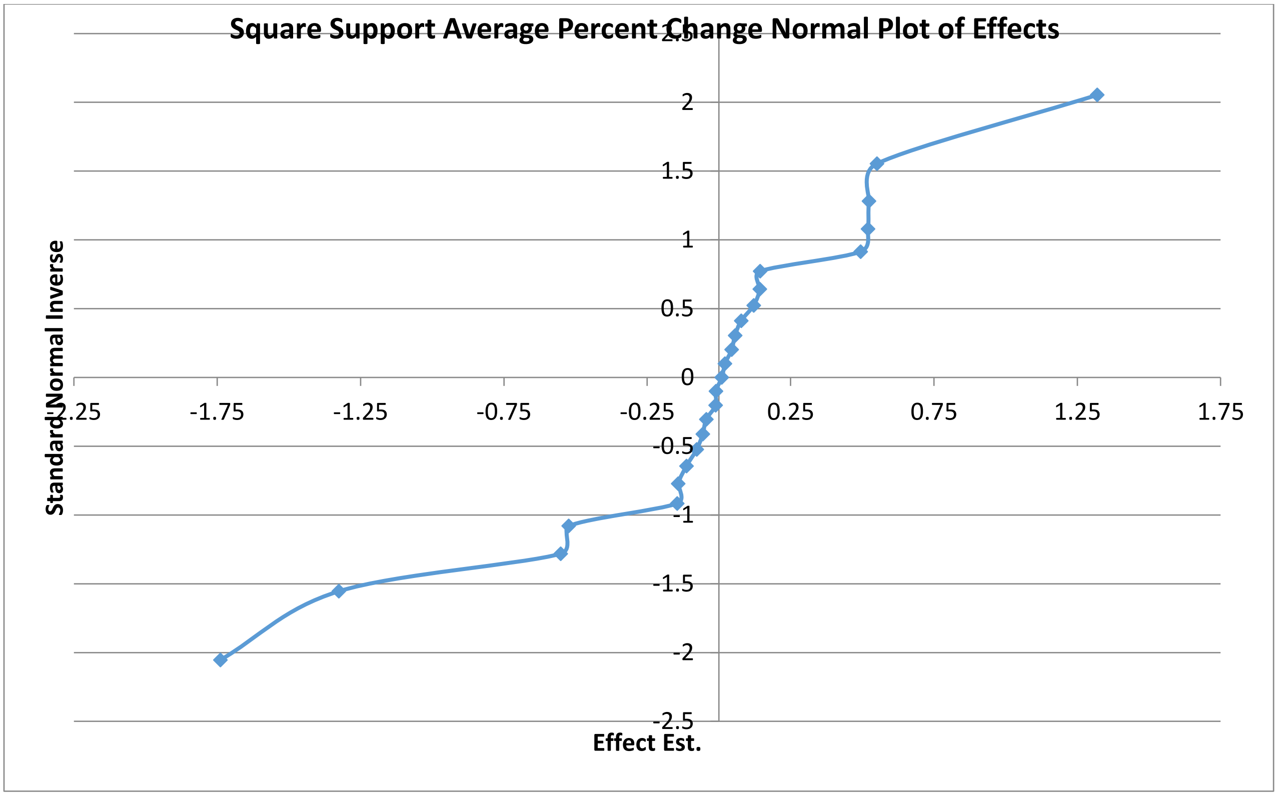
Percentile Correlation

Factor	Sorted Effects	Standard Normal Inverse
BC	-0.23	-2.053748911
AC	-0.22	-1.554773595
AB	-0.19	-1.281551566
D	-0.13	-1.080319341
BE	-0.12	-0.915365088
AE	-0.10	-0.772193214
F	-0.08	-0.643345405
AG	-0.05	-0.524400513
CE	-0.04	-0.412463129
BG	-0.04	-0.305480788
CG	-0.03	-0.201893479
DE	-0.02	-0.100433721
BD	-0.02	0
AD	0.00	0.100433721
BF	0.00	0.201893479
AF	0.02	0.305480788
G	0.03	0.412463129
E	0.04	0.524400513
CF	0.08	0.643345405
DG	0.09	0.772193214
CD	0.13	0.915365088
DF	0.19	1.080319341
A	0.22	1.281551566
B	0.23	1.554773595
C	0.43	2.053748911


Square Support Percentile Correlation Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50

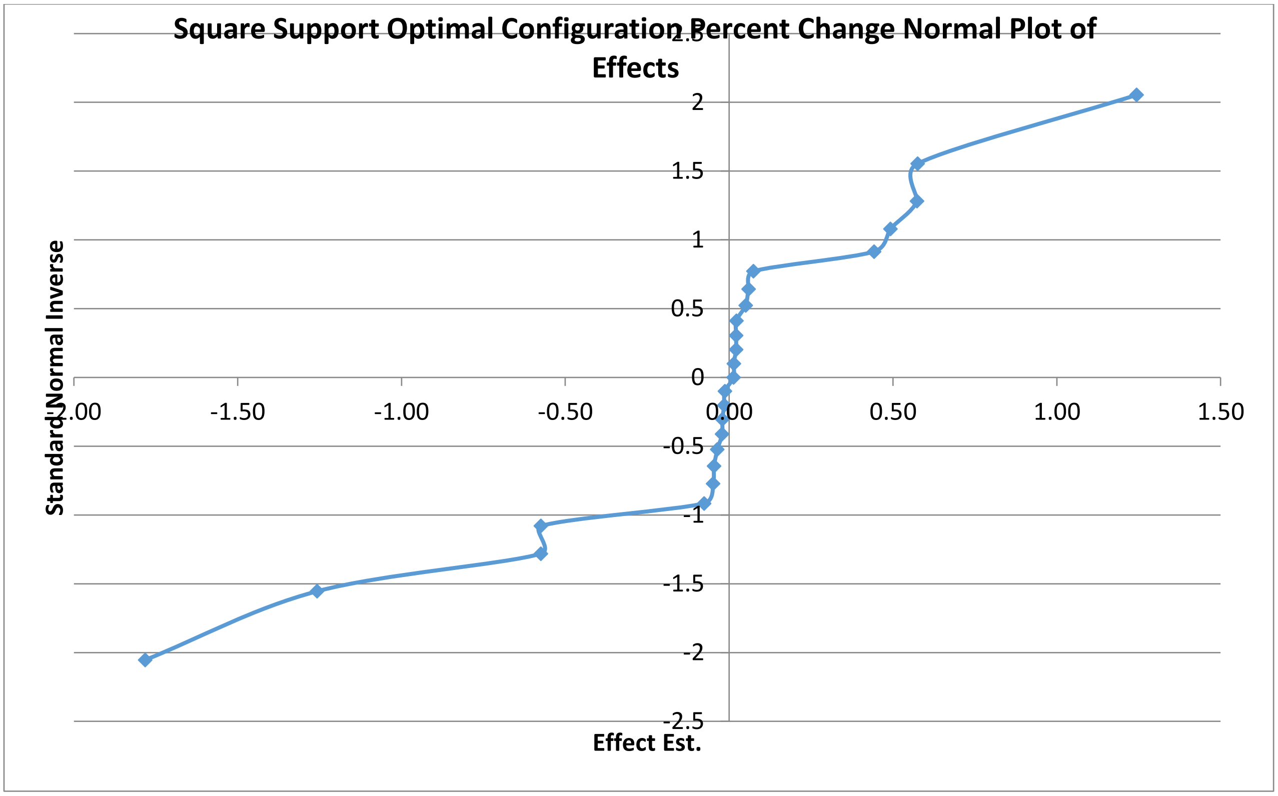
Average Percent Change

Factor	Sorted Effects	Standard Normal Inverse
C	-1.74	-2.053748911
A	-1.33	-1.554773595
G	-0.55	-1.281551566
E	-0.52	-1.080319341
AB	-0.14	-0.915365088
BC	-0.14	-0.772193214
BE	-0.11	-0.643345405
BF	-0.08	-0.524400513
D	-0.06	-0.412463129
CF	-0.04	-0.305480788
BG	-0.01	-0.201893479
AF	-0.01	-0.100433721
BD	0.01	0
DE	0.02	0.100433721
F	0.04	0.201893479
CD	0.06	0.305480788
AD	0.08	0.412463129
DG	0.12	0.524400513
B	0.14	0.643345405
DF	0.14	0.772193214
AE	0.50	0.915365088
AG	0.52	1.080319341
CE	0.52	1.281551566
CG	0.55	1.554773595
AC	1.32	2.053748911


Square Support Average Percent Change Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2.25
-1.75
-1.25
-0.75
-0.25
0.25
0.75
1.25
1.75

Optimal Configuration Percent Change

Factor	**Sorted Effects**	**Standard Normal Inverse**
C	-1.78	-2.053748911
A	-1.26	-1.554773595
G	-0.57	-1.281551566
E	-0.57	-1.080319341
DF	-0.08	-0.915365088
CF	-0.05	-0.772193214
DE	-0.05	-0.643345405
BE	-0.04	-0.524400513
D	-0.02	-0.412463129
B	-0.02	-0.305480788
AF	-0.02	-0.201893479
AD	-0.01	-0.100433721
BF	0.01	0
BD	0.01	0.100433721
CD	0.02	0.201893479
BG	0.02	0.305480788
BC	0.02	0.412463129
F	0.05	0.524400513
DG	0.06	0.643345405
AB	0.07	0.772193214
AE	0.44	0.915365088
AG	0.49	1.080319341
CG	0.57	1.281551566
CE	0.58	1.554773595
AC	1.24	2.053748911


Square Support Optimal Configuration Percent Change Normal Plot of Effects
Standard Normal Inverse
Effect Est.
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50

Appendix I Numerical Responses for Treatment Combinations

Appendix I.1. Bearing Block Treatment Combinations

Scenario Number	Factor Levels				Average Response Values			
	Part Volume	**Material Cost**	**Load/Unload Time**	**Labor Rate**	**Rank Correlation**	**Percentile Correlation**	**Average Percent Change**	**Optimal Configuration Percent Change**
1	-1	1	1	1	0.62	0.39	28.98%	21.93%
2	-1	1	1	-1	0.18	0.66	36.33%	52.06%
3	-1	1	-1	1	0.05	0.73	35.62%	51.60%
4	-1	1	-1	-1	0.08	0.71	37.41%	54.08%
5	-1	-1	1	1	0.84	0.82	97.38%	45.44%
6	-1	-1	1	-1	0.75	0.75	321.72%	275.70%
7	-1	-1	-1	1	0.07	0.19	256.15%	274.80%
8	-1	-1	-1	-1	0.24	-0.03	473.99%	481.03%

Appendix I.2. Square Support Treatment Combinations

Scenario Number	Factor Levels				Average Response Values			
	Part Volume	Material Cost	Load/Unload Time	Labor Rate	Rank Correlation	Percentile Correlation	Average Percent Change	Optimal Configuration Percent Change
1	-1	1	1	1	0.82	0.77	32.45%	28.94%
2	-1	1	1	-1	0.41	0.70	45.69%	52.44%
3	-1	1	-1	1	0.22	0.76	45.01%	62.44%
4	-1	1	-1	-1	0.33	0.92	44.66%	71.84%
5	-1	-1	1	1	0.82	0.68	92.02%	89.32%
6	-1	-1	1	-1	0.35	0.32	317.21%	315.34%
7	-1	-1	-1	1	0.25	0.20	306.83%	305.74%
8	-1	-1	-1	-1	0.28	0.22	510.02%	506.00%

References

Beleiciks, N., & Bechtoldt, F. (2018, June 28). Oregon’s Minimum Wage Increases on July 1, 2018. Retrieved July 29, 2018, from https://www.qualityinfo.org/-/oregon-s-minimum-wage-increases-on-july-1-2018

Box, G. E. P., Hunter, J. S., & Hunter, W. G. (2005). *Statistics for Experimenters: Design, Innovation, and Discovery, 2nd Edition* (2nd edition). Hoboken, N.J: Wiley-Interscience.

Chan, R., Haapala, K. R., & Campbell, M. I. (2018). ASSESSING COMPONENT MACHINABILITY USING VOXELIZED SOLID MODELS, 8.

Fu, W., Eftekharian, A. A., & Campbell, M. I. (2013). Automated Manufacturing Planning Approach Based on Volume Decomposition and Graph-Grammars. *Journal of Computing and Information Science in Engineering, 13*(2), 021010. https://doi.org/10.1115/1.4023860

George Goehl. (2012). *Silver Soldering a Lap Joint in Copper*. Retrieved from https://www.youtube.com/watch?v=n3bNkpeoPDE

Heragu, S. S. (2016). *Facilities Design, Fourth Edition* (4th ed.). Milton, UNITED KINGDOM: CRC Press. Retrieved from http://ebookcentral.proquest.com/lib/osu/detail.action?docID=4648057

Hoefer, M., Chen, N., & Frank, M. (2017). Automated Manufacturability Analysis for Conceptual Design in New Product Development (p. 7). Presented at the Industrial and Systems Engineering Research Conference.

Hoist and Trolley Full Catalog. (2017). Columbus McKinnon Corporation. Retrieved from https://www.cmworks.com/Public/11144/Hoist%20and%20Trolley%20Full%20Catalog.pdf

Kulturel-Konak, S., Smith, A. E., & Norman, B. A. (2004). Layout optimization considering production uncertainty and routing flexibility. *International Journal of Production Research*, *42*(21), 4475–4493. https://doi.org/10.1080/00207540412331325567

Machines. (n.d.). Retrieved July 29, 2018, from http://www.thompson-friction-welding.com/index.php/machines

Manufacturing Technology Inc (MTI). (2016). *Inertia Friction Welder for Aerospace Component - Model 480B*. Retrieved from https://www.youtube.com/watch?v=42MUVQNPrXE

Massoni, B. R., & Campbell, M. I. (2017a). A decomposition method for efficient manufacturing of complex parts. *Computer-Aided Design and Applications*, *14*(6), 705–719. https://doi.org/10.1080/16864360.2017.1287673

Massoni, B. R., & Campbell, M. I. (2017b). Optimizing Cutting Planes for Advanced Joining and Additive Manufacturing. *Journal of Manufacturing Science and Engineering*, *140*(3), 031001-031001–031009. https://doi.org/10.1115/1.4038509

Mechanical Engineers. (2017, May). Retrieved July 29, 2018, from https://www.bls.gov/oes/current/oes172141.htm

MetalMiner Prices: Carbon Steel Prices. (n.d.-a). Retrieved July 25, 2018, from https://agmetalminer.com/metal-prices/carbon-steel/

MetalMiner Prices: Titanium Prices. (n.d.-b). Retrieved July 25, 2018, from https://agmetalminer.com/metal-prices/titanium/

Montgomery, D. C. (2012). *Design and Analysis of Experiments* (8 edition). Hoboken, NJ: Wiley.

NIST/SEMATECH e-Handbook of Statistical Methods. (2012). Retrieved from http://www.itl.nist.gov/div898/handbook/

Palekar, U. S., Batta, R., Bosch, R. M., & Elhence, S. (1992). Modeling uncertainties in plant layout problems. *European Journal of Operational Research*, *63*(2), 347–359. https://doi.org/10.1016/0377-2217(92)90035-8

Pushing & Pulling - Handcarts. (2018, March 1). Retrieved August 4, 2018, from http://www.ccohs.ca/

Rosenblatt, M. J. (1986). The Dynamics of Plant Layout. *Management Science*, *32*(1), 76–86. https://doi.org/10.1287/mnsc.32.1.76

Salary.com, S. built by: (2018, July 31). Hourly wage for Warehouse Worker. Retrieved August 4, 2018, from https://www1.salary.com/Warehouse-Worker-hourly-wages.html

Sinkora, E. (2018, April 23). New Tool Designs Power Faster-Than-Ever Cutting. Retrieved July 27, 2018, from https://advancedmanufacturing.org/new-tool-designs-power-faster-than-ever-cutting/

Yang, T., & Kuo, C. (2003). A hierarchical AHP/DEA methodology for the facilities layout design problem. *European Journal of Operational Research*, *147*(1), 128–136. https://doi.org/10.1016/S0377-2217(02)00251-5

Zelinski, P. (2010, February 12). The Promise of “High Cube” Machining. Retrieved October 1, 2018, from https://www.mmsonline.com/articles/the-promise-of-high-cube-machining