

# MAPPING CONTEXT AND INTERDEPENDENCY IN TECHNOLOGY SELECTION: A PROCESS-BASED COST MODEL FOR PRODUCT ASSEMBLY

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## ABSTRACT

Within product development, designers must specify not only product form, but also materials and manufacturing process. The implications of these choices are interdependent and, with reference to financial implications, context dependent. This paper presents a generative cost model, implemented using the methods of process-based cost modeling (PBCM), which comprehends these issues for a specific activity – serialized assembly. The model operates on relatively limited data and can, and has been, applied to early stage PD decisions. A representative, hypothetical case study of automobile body construction is used to demonstrate the usefulness of PBCM to inform both design and technology strategy decisions.

## Keywords

Process-Based Cost Model, Assembly Process, Product Development

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# 1. Introduction

As we learn more about the product development process, a universal characteristic that emerges is the fundamental interdependence of the decisions required to conceptualize, create, and distribute a product. The earliest concepts of product form and performance influence the selection of forming technologies, which together drive the choice of materials to create those forms. Material and manufacturing technology determine the set of potential component vendors and, therefore, the possible composition and configuration of the supply chain. The complexity of this web of interrelated decisions makes fully informed decision-making seem intractable especially at the early, strategic stages of design when details are scarce. Nevertheless, key decisions must be made and made early, to avoid the costs of redundant detailed design.

Fortunately, a range of models and computer tools have been developed to inform product development decisions. Not surprisingly, given its critical role in business decisions, many of these tools incorporate cost, in some form, as a decision metric. However, in most cases, cost is incorporated as a single figure or as simple monotonic relationship based on a few decision variables. Firms do eventually project the cost consequences of the complete set of design decisions through detailed cost estimates. However, for most firms this process occurs late in the design cycle and is time consuming. A number of authors have specifically criticized the absence of real-time, detailed cost evaluation for design activities, concluding that such separation leads to either cost constraints, which limit design options, or asynchronous cost estimation and expensive iterative redesign (Noble and Tanchoco 1990 [1], Wei and Egbelu 2000 [2], Field, et al. 2001 [3]).

Ultimately, decision-makers need methods that (1) allow them to explore the economic consequences of their design decisions, (2) are sensitive to business specific context<sup>2</sup>, (3) can provide insight into the interdependencies of key design decisions, and (4) can provide insight early in the design cycle. (Noble and Tanchoco 1990 [1], Asiedu and Gu 1998 [4]) Although no method addresses all of these needs completely, this paper presents a generative cost model which can provide quantitative insight into production cost across most of the dimensions of the decision space described above including the technological— materials, architecture, and process; operational— location and automation; and strategic — platforming and volume. To accomplish this, the model captures some key interdependencies among product and process design even with limited early-stage design detail.

The focus of the model is on an activity central to realizing any complex product — assembly. The underlying modeling method can and has been applied to a range of part production technologies. Although, the model presented herein was developed to support strategic decisions for the automobile, it is readily extensible to any form of serializable<sup>3</sup> assembly.

This paper begins with a survey of research examining assembly cost in the context of a number of design decisions. This is followed by a review of the use of generative models, in general, and of the method applied specifically herein — process-based cost modeling. Then it details the proposed

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<sup>2</sup> All measures of performance are sensitive to the context in which they are measured. However, more than any other widely applied engineering decision criteria cost is intensely dependent on context. Key contextual conditions include production scale, manufacturing and market location, prevailing factor costs, and risk tolerance of the firm.

<sup>3</sup> Throughout this paper serializable assembly refers to operations where throughput requirements are met by splitting tasks among stations operating in series, not replicated in parallel.

assembly cost model. The final section discusses the result of a hypothetical case study, with particular focus on the implications for the usefulness of the described tool. In the end, this paper will demonstrate that 1) to evaluate the cost preferred design, decision-makers must simultaneously consider the impact of product design (architecture / form), material, process, and context and 2) that process-based generative models can be used to provide that insight based on limited design details and, therefore, during the early strategic stages of development.

## 2. Cost in Product Development Decision-Making

Cost models and cost as a decision metric in models are discussed in many instances throughout the operations and product development literature. A thorough survey of this topic in supporting development decisions can be found in Noble and Tanchoco. (1990 [1], 1993 [5]) The following section surveys those works that have explored the specific implications of assembly cost. A focus is placed on the ability of such models to evaluate simultaneously various aspects of development and sensitivity to strategic and operational context.

### 2.1. PRODUCT DESIGN

In today's technology driven marketplace, the importance of design is unquestioned; design not only establishes functional performance, but also drives economic characteristics. (Bhimani and Mulder 2001 [6], Boothroyd, et al. 1993 [7], Shehab and Abdalla 2001 [8]) Pioneering work to develop methods that map the economic characteristics of assembly alternatives was carried out by Boothroyd and Dewhurst in the development of the concepts and tools of DFM (Design for Manufacturing) and DFA (Design for Assembly). (Boothroyd 1982 [9], Boothroyd, et al. 1988(a) [10]) These methods have been used to identify design improvements within both mechanical and electronic assemblies. (Boothroyd and Reynolds 1988(b) [11], Leclerc and Subbarayan 1996 [12]) In all reported cases, the DFM/A methods proved to be capable of identifying design options that reduced manufacturing cost.

Several authors have used various other cost-estimating methods for assembly activities to support design decisions. Alexander et al. (1994 [13]) developed a knowledge based cost model to evaluate technologies for populating printed circuit boards . Ball et al. (1995 [14]) used mathematical programming methods to identify the least cost combination of product and process design. Leclerc and Subbarayan (1996 [12]) developed a cost estimation methodology to evaluate the suitability of a photonic systems design for efficient optical, electronic and mechanical assembly. In each of the above cases, cost is assessed according to the form:

$$UnitCost = t \times \left( Labor\ Rate + \frac{Equipment\ Investment}{Production\ Volume} \right) + Materials + \frac{Tool\ Investment}{Production\ Volume} \quad (1)$$

in which, cycle time ( $t$ ), equipment investment, materials, and tool investment can be a function of the product design and assembly technology. Inefficiencies due to poor utilization, defective assemblies, or other production losses were accounted for variously, but in all cases, these inefficiencies were not modeled as a function of the decision variables. This simplified treatment of operational inefficiency significantly improves computational efficiency and is appropriate for evaluating decisions with relatively limited operational scope and/or high technological flexibility. For early stage strategic decisions within a firm with a large operational and product footprint or for those firms considering outsourcing, this limitation could lead to erroneous results. Furthermore, as will be

demonstrated specifically later, this assumption is inconsistent with the operational behavior of serialized assembly – the case focus of this work.

### **2.1.1. Materials Decisions**

Within the product development process, materials choice is one of the most fundamental decisions. Given this importance, a range of literature has proposed methods to identify promising materials candidates. (Farag 1989 [15], Trethewey, et al. 1998 [16], Ashby 1999 [17], Jee and Kang 2000 [18], Amen and Vomacka 2001 [19], Ermolaeva, et al. 2002 [20], Edwards 2005 [21], Shanian and Savadogo 2006 [22]) Although most of these discuss cost as important, none provide specific methods to understand the impact of assembly cost.

A few case oriented papers have bridged this gap. Boothroyd demonstrated that a near net shaped nylon component could reduce cost compared to a steel design despite higher materials costs. (Boothroyd, et al. 1988(a) [10]) A similar result is discussed in Cramer and Taggart (2002 [23]). Butrie's analysis (Butrie 1994 [24]) of laser module designs provides another example of the importance of assembly cost on material selection.

Models used in these works provide excellent tools to evaluate design decisions within specific operational constraints, but, as described above, the lack of explicit operational detail limits their extension to serialized assembly and their applicability to broadly defined strategic questions.

## **2.2. ASSEMBLY PROCESS DESIGN**

Assembly process design includes both the allocation of available resources (i.e., equipment, labor, etc.) to assembly operations as well as the selection of the specific assembly technologies and resources that best suit firm objectives. With process design generally conceptualized as occurring later in the product development cycle, tools to support process design decisions have largely been built to leverage the more complete design detail available at that time. While such methods may not be directly applicable to earlier questions, it is critical to identify those elements of assembly process design that can be captured in early stage analysis. In doing so, it should be possible to create a more robust model; a model that more accurately reflects the interdependency of design, material, and production process decisions.

A large body of work exists that has examined the optimal assignment of assembly tasks to assembly resources (Graves and Whitney 1979 [25], Graves and Lamar 1983 [26], Bukchin and Tzur 2000 [27], Lee 1999 [28]). Extensive surveys about work in this area can be found in Erel (1998 [29]) and Rekiek, Dolgui, et al. (2002 [30]). Generally, the approaches taken in these papers use sophisticated analytical methods to provide detailed, quantitative information on the preferred assembly process design. However, the need for detailed process information (e.g., task time, sequence, and equipment requirement) make these models difficult to apply during the early design stage. These models typically use implicit or simple cost functions that may not resolve cases with significant scope in technology or operational practice.

Additionally, a number of approaches have been proposed to address technology selection considering the complex coupling between characteristics of the design, the material and the process technology, as reviewed by Shercliff and Lovatt.(2001 [31]). Although some of these

approaches can be applied with only limited design information, the focus of these methods has been on part production and technical evaluation; there have been few papers to address cost implications and even fewer that comprehend the implications of production context (e.g., scale or prevailing wage).

Boothroyd's work (1982 [9]) provides an example that addresses that gap in that it compares the economic performance of manual, special purpose automatic, and programmable assembly systems. Gustavson's unit-cost-to-produce analysis extends Boothroyd's work through more operationally detailed evaluation of a similar set of assembly technologies. (Gustavson 1983 [32], Gustavson 1988 [33]). Similarly, Koelemeijer-Chollet et al. (2003 [34]) similarly proposed an assembly cost model for microsystems assembly cost and analyzed the economics of manual, flexible automated, and dedicated automated processes. The models used in each of these analyses rely on detailed descriptions of the assembly task under evaluation. Although, in doing so, these models may not be directly applicable to early strategic decisions, they provide a clear template on how to comprehend the cost implications of changes in operation and technology for early stage analysis.

The model presented herein extends the latter family of work through the use of a generative cost model that provides the ability to (1) map from limited product design information to estimated assembly processing requirements, (2) select technology for the assembly of interest based upon explicit assessment of resource requirements for the specified operational and financial context, and (3) capture the specific operational behavior of serializable assembly.

### 3. Review of Cost Modeling Approach

A range of methods, collectively referred to as Technical Cost Modeling (TCM), have been proposed to examine the economic implications of various technological options within product development. Specifically, TCM methods attempt to accomplish this by projecting the economic consequences of a process or product before it has been executed or produced.

There are two widely recognized approaches to TCM. Variant cost modeling uses similarities between current and past products or processes to project costs (e.g., (Daschbach and Apgar 1988 [35])). In contrast, generative cost modeling projects costs based on details of production requirements and operational conditions (Asiedu and Gu 1998 [4], Weustink, et al. 2000 [36]). The fact that variant-based costing relies on previous products makes it less useful for new technologies, products, or operational conditions. Given the breadth of options available at the early, strategic phase of product development, a generative approach was selected.

Notably, several generative models have been proposed for use in cost estimation of both manufacturing and assembly. (Noble and Tanchoco 1990 [1], Wei and Egbelu 2000 [2], Shehab and Abdalla 2001 [8], Leibl, et al. 1999 [37], Boothroyd, et al. 1994 [38]). Across these cases, authors make use of a range of approaches, but in each, engineering information is used to derive estimates of the economic consequence of the specific manufacturing activity. As discussed in the preceding section, the model presented herein extends these works by providing a mechanism to map economic consequence from limited product description and to capture operational context sensitivity for serializable assembly.

While no standard method of generative cost modeling is widely used and accepted, one that meets the requirements, as outlined above, of Noble and Tanchoco and Asiedu and Gu and that is applied

herein is Process-Based Cost Modeling (PBCM). PBCM was developed to analyze the economics of emerging manufacturing processes without the prohibitive economic burdens of trial and error innovation (Busch and Field 1988 [39]). Its application has been extended to the implications of alternative design specifications and process operating conditions on production costs within and across manufacturing processes (Kirchain and Field 2000 [40]). Specifically, PBCMs project cost consequences by building up an estimate from details of the production process. The PBCM, using basic engineering principles and industry data, first estimates required processing conditions. These estimates are used to project the quantity of production resources such as capital, labor, materials, and energy required to satisfy a specified production target. These resource requirements can be mapped to corresponding operating and investment expenses and then aggregated into unit cost. In the same way that present-day engineering models allow designers and manufacturing engineers to understand the physical consequences of their technical choices before those choices are put into action, PBCM harness the engineering approaches at work within these physical models to avoid expensive strategic errors in product development and deployment.

Aside from the fundamental benefit of providing insight into novel technologies, PBCMs offer four specific benefits for strategic design questions. These benefits are:

- 1) Identifying cost drivers

Armed with knowledge of key technological and operational drivers of cost, firms can focus development effort on their improvement or elimination. PBCMs can provide a novel insight into this issue, insofar as they are able to quantify relevant costs for both current and prospective production.

- 2) Quantifying necessary process performance hurdles

Because PBCMs build cost up from technological causes, it is possible to use these models to explore the impact of changing technological conditions. This information quantifies the level of manufacturing performance that is required to bring costs to targeted levels.

- 3) Quantifying impact of changes in production context

If developed with sufficient detail and fidelity, PBCMs can generate invaluable analysis on the impact of changes in the non-technological conditions of production on ultimate production cost. This is particularly useful for early stage strategy decisions, where prospective modes of production are broad and may span not only form and process, but also markets and regions.

- 4) Generic platform to discuss cost of process / product developments

The final benefit of the PBCMs is that it provides a common platform which can be used to discuss cost issues. Because product development projects must incorporate the views of diverse stakeholders, often including those outside of the OEM, they may falter as individuals try to discuss issues based on different accounting perspectives. Because PBCMs can be constructed in a transparent manner, it is possible for all involved to focus decision-making on the underlying drivers and implications of cost, rather than on the method of computing those values. These benefits will be illustrated through the use of a case analysis of an automotive assembly process. The following section first describes the PBCM of serialized assembly applied in that case.

## **4. Description of MIT/MSL PBCM for assembly process**

The MIT/MSL assembly PBCM allows a user to project and analyze the cost of assembling a multi-component, multi-subassembly product using a serialized line. As will be detailed, the model attempts to project the efficient fabrication line, requiring minimum resources, that is capable of assembling a defined annual volume of good products and then calculates the cost of installing and operating that line. Because any given assembly operation can be realized with a range of technological options (e.g., manual or robotic), the model also selects the lowest cost set of assembly technologies for the case of interest. To accomplish this, the model executes iteratively, first evaluating approximate economics of the technological options, then evaluating the full economics of the line composed with the economically preferred technology. Paralleling this approach, the following description will focus on how the model derives cost of an assembly line while the detailed description about how the model projects the assembly line configuration is provided in APPENDIX.

For the sake of clarity, several simplifying assumptions have been made in the subsequent presentation of the model. These well reflect the operational conditions of automotive body assembly (the focus of the later case study) and many other modern assembly processes. These assumptions include: (1) Assembly occurs progressively and sequentially with all activities in series; (2) All assembly stations operate without yield loss and at the same cycle time; and (3) Non-reusable capital is dedicated to the production of only the product under analysis. Where appropriate, equations will be noted that would need to be modified to accommodate variations from these assumptions.

#### 4.1. OVERARCHING NOMENCLATURE

The model is organized around the construction of subassemblies, referred to as *Groups* ( $i$ ), where  $\mathcal{I}$  represents the set of all Groups in the assembly of interest. Groups are assembled using joining *Methods* ( $j$ ), where  $\mathcal{J}$  is the set of all available Methods. Each method is realized through the coordinated efforts of several pieces of equipment (e.g., rivet gun, robot, and rivet feeder). Several possible combinations of equipment can be used to execute a given method (e.g., (A) rivet gun + robot + automotive feeder vs. (B) rivet gun + manual operator + manual feeder). A collection of equipment that makes a method feasible is referred to as an *Instance*  $\xi$ . The union of such collections for all the available methods is denoted as:

$$\Xi = \{[p, d, f, t, l] \mid p \in \mathcal{P}, d \in \mathcal{D}, f \in \mathcal{F}, t \in \mathcal{T}, l \in \mathcal{L}\}$$

where  $\mathcal{P}, \mathcal{D}, \mathcal{F}, \mathcal{T}, \mathcal{L}$  are the sets for positioning equipment, dispensing equipment, material feeding equipment, transportation equipment and loading equipment respectively. Table 1 provides a definition of these types of equipment.

The final cost of producing the assembly of interest, referred to as total unit cost,  $C_{unit}^{total}$ , is calculated simply according to:

$$C_{unit}^{total} = \frac{C_{annual}^{total}}{V} = \sum_i C_{annual,i}^{total} / V \quad (2)$$

where  $C_{annual}^{total}$  is the total annual cost associated with an assembly and  $V$  is the annual production volume of good assemblies.  $C_{annual,i}^{total}$  is the total unit cost of assembly for Group  $i$ , which aggregates costs of resources required by Group  $i$ , including material<sup>4</sup>, energy, labor, overhead, equipment, tool, and building, shown in Equation (3) below. For simplicity,  $C_{annual,i}^{total}$  is subsequently abbreviated as  $C_i^{total}$  :

$$C_i^{total} = C_i^{material} + C_i^{energy} + C_i^{labor} + C_i^{overhead} + C_i^{equip} + C_i^{tool} + C_i^{building} \quad (3)$$

The discussion in this section will center around  $C_i^{total}$  since, as shown in Equation (2),  $C_{unit}^{total}$  is simply an aggregation of  $C_i^{total}$  for all groups. To arrive at  $C_i^{total}$ , the model first evaluates for each method in Group  $i$  all feasible technological instances. Subsequently,  $\widehat{C_{ij\xi}^{total}}$ <sup>5</sup> is used to denote the total *annual* cost ascribed to an instance of equipment collection  $\xi$  utilized by Method  $j$  in Group  $i$  and comprises elements analogous to those in Equation (3). Thus, the equation to calculate  $\widehat{C_{ij\xi}^{total}}$  is:

$$\widehat{C_{ij\xi}^{total}} = \widehat{C_{ij\xi}^{material}} + \widehat{C_{ij\xi}^{energy}} + \widehat{C_{ij\xi}^{labor}} + \widehat{C_{ij\xi}^{overhead}} + \widehat{C_{ij\xi}^{equip}} + \widehat{C_{ij\xi}^{tool}} + \widehat{C_{ij\xi}^{building}} \quad (4)$$

Using this quantity, the model selects the most economically efficient technological instance, namely,  $\xi_{ij}^* = \arg \min_{\xi} \left\{ \widehat{C_{ij\xi}^{total}} \right\}$ . Finally, the  $C_i^{total}$  are calculated based on the respective  $\xi_{ij}^*$  by Equation (3), with the calculation of the cost elements on the right side of the equation detailed as follows.

## 4.2. COST FOR MATERIAL, ENERGY, LABOR AND OVERHEAD

Material costs are driven by consumption rates per join and the required amount of a joining. Within the model, these consumable materials include welding gases, small fasteners, adhesives, etc. Therefore, the annual cost for materials for Method  $j$  in Group  $i$  required by a collection of equipment  $\xi$  ( $\widehat{C_{ij\xi}^{material}}$ ) is :

$$\widehat{C_{ij\xi}^{material}} = \sum_k R_{k\xi_{ij}}^m \times n_{ij} \times P_k^m \times V \quad (5)$$

Where  $R_{k\xi_{ij}}^m$  is the consumption rate of the  $k^{\text{th}}$  type of material associated with  $\xi$ .  $n_{ij}$  is the joining intensity (i.e., meters or joins) of Method  $i$  required by Group  $i$  per product, and  $P_k^m$  is the price per unit of material  $k$ .

<sup>4</sup> Materials here do not represent parts that are assembled, but rather those materials that are used to realize a joint.

<sup>5</sup> The notation ( $\widehat{\circ}$ ) indicates a quantity or cost used for optimal technology selection. Notation without modification indicates a calculation used for final cost.



After the preferred instance  $\xi_{ij}^*$  is selected for each method in Group  $i$ , the final annual material cost for Group  $i$  is calculated as:

$$C_i^{material} = \sum_j \widehat{C}_{ij\xi^*}^{material} \quad (6)$$

Energy costs are based on the quantity of energy consumed and the unit price of energy. The current model focuses on electricity, but is readily extensible to other sources of energy. The calculation of energy cost required by a collection of equipment  $\xi$  for Method  $j$  in Group  $i$  is:

$$\widehat{C}_{ij\xi}^{energy} = \left( \widehat{EN}_{ij\xi}^P + \widehat{EN}_{ij\xi}^D + \widehat{EN}_{ij\xi}^F + \widehat{EN}_{ij\xi}^T + \widehat{EN}_{ij\xi}^L \right) \times P^{en} \times V \quad (7)$$

where  $P^{en}$  is the unit price for energy. The  $\widehat{EN}_{ij\xi}^o$  s are the energies required for respective elements of  $\xi$  with  $o$  representing P for positioning equipment, D for dispensing equipment, F for material feeding equipment, T for transportation equipment and L for part loading equipment<sup>6</sup>, respectively. Detailed calculations of the  $\widehat{EN}_{ij\xi}^o$  s are provided in the APPENDIX.

Then the equation for calculation of final energy cost for Group  $i$  is:

$$C_i^{energy} = \left( \sum_j \left( \widehat{EN}_{ij\xi^*}^P + \widehat{EN}_{ij\xi^*}^D + \widehat{EN}_{ij\xi^*}^F \right) + EN_i^T + \widehat{EN}_{i\xi^*}^L \right) \times P^{en} \times V \quad (8)$$

The  $\widehat{EN}_{ij\xi^*}^o$  s are calculated based on the characteristics of the selected equipment,  $\xi_{ij}^*$ , but otherwise are equivalent to those used in Equation (7). The calculation of  $EN_i^T$  differs from that used for technology selection insofar as to comprehend the transport of subassemblies of between stations with that utilize more than one joining method. Specifically, the final energy consumptions related to transportation are modelled as the weighted average of the energy consumptions associated with the methods in mixed stations as indicated in Equations (62) to (64).

Labor in the assembly process are differentiated as direct labor and indirect labor. Direct labor includes 1) those workers charged with tasks that directly manipulate components, such as assembly, rework and finishing, quality inspection, and materials handling; 2) team leaders who play a supervisory role on the line; and 3) allocation for coverage of absentee workers. Indirect labor includes group leaders and maintenance workers. Labor cost,  $C^{labor}$ , accounts for the cost associated with direct labor while the cost for indirect labor is included as part of the overhead cost  $C^{overhead}$  which will be discussed later. Labor cost is determined by the number of workers employed, the annual paid hours, and the labor rate, according to the equation:

$$\widehat{C}_{ij\xi}^{labor} = \left( Wage_{normal} \times APT_{normal} + Wage_{OT} \times APT_{OT} \right) \times \widehat{N}_{ij\xi}^{lb} \quad (9)$$

<sup>6</sup> The same conventional is kept for the rest of the paper.

Where  $Wage_{normal}$  and  $Wage_{OT}$  are the average, fully-loaded hourly wage of a worker during normal operating time and overtime respectively;  $APT_{normal}$  and  $APT_{OT}$  are annual paid time during normal operating hours and during overtime, which are calculated as:

$$APT_{normal} = (H_{shift} - H_{unpdBk}) \times Sft \times D \quad (10)$$

$$APT_{OT} = H_{OT} \times D \quad (11)$$

where  $H_{shift}$  is the operation time in hours per shift;  $H_{unpdBk}$  is the time in hours for unpaid breaks per shift;  $Sft$  is the number of daily production shifts;  $D$  is the operating days per year; and  $H_{OT}$  is the time in hours for overtime production per day. Figure 1 illustrates graphically the interrelation of these various aspects of production time as comprehended within the model.

The final labor cost for Group  $i$  is calculated as:

$$C_i^{labor} = (Wage_{normal} \times APT_{normal} + Wage_{OT} \times APT_{OT}) \times N_i^{lb} \quad (12)$$

The calculations for  $\widehat{N}_{ij\xi}^{lb}$ , the quantity of direct labors required by  $\xi$  for Method  $j$  in Group  $i$ , and  $N_i^{lb}$ , the final needed direct labors for Group  $i$ , differ insofar as the latter accounts for stations with multiple joining methods. Details are provided in the APPENDIX.

Overhead cost includes indirect labor costs and other maintenance expenses such as hardware and consumable materials. The number of maintenance workers is calculated as proportional to the number of assembly workers. The total number of group managers is modeled as proportional to the number of groups in the assembly process. Similarly, the other expenses for maintenance are modeled as proportional to the annual investment cost for equipment, tooling and building. As such, the equation for the overhead cost for Method  $j$  in Group  $i$  used within the model is:

$$\widehat{C}_{ij\xi}^{overhead} = (Wage_{normal} \times APT_{normal} + Wage_{OT} \times APT_{OT}) \times \omega_{mtn} \times \widehat{N}_{ij\xi}^{lb,assm} + \varepsilon \times (\widehat{C}_{ij\xi}^{equip} + \widehat{C}_{ij\xi}^{tool} + \widehat{C}_{ij\xi}^{building}) \quad (13)$$

Where  $\omega_{mtn}$  is the ratio between maintenance workers and assembly workers;  $\varepsilon$  is the ratio between non-labor maintenance expense and the annual investment cost for equipment, tooling and building.

Adding the cost for group managers in Group  $i$ , the final calculation for overhead cost in Group  $i$  thus is:

$$C_i^{overhead} = \sum_j \widehat{C}_{ij\xi}^{overhead} + \omega_{gm} \times (Wage_{normal} \times APT_{normal} + Wage_{OT} \times APT_{OT}) \quad (14)$$

where  $\omega_{gm}$  is the average number of group managers per group.

### 4.3. ANNUAL COST FOR EQUIPMENT, TOOL AND BUILDING

In contrast to expenditures for material, energy and labor, expenditures for capital occur at a frequency much slower than the rate of production. To compare these different cost patterns, it is useful to annualize capital costs, which can then be easily distributed over  $V$ .

#### 4.3.1. Annual cost for equipment

Annual cost for equipment is the aggregated annual cost for all five categories of equipment:

$$\widehat{C}_{ij\xi}^{equip} = \left( \widehat{C}_{ij\xi}^{eq,P} + \widehat{C}_{ij\xi}^{eq,D} + \widehat{C}_{ij\xi_f}^{eq,F} + \widehat{C}_{ij\xi_t}^{eq,F} + \widehat{C}_{ij\xi_l}^{eq,L} \right) \times PL \quad (15)$$

Where  $PL$  is the number of parallel lines needed to meet production goals, which is further detailed in APPENDIX.

For each type of equipment, cost is determined by the quantity required to meet production goals and the annualized unit price of the equipment. These are computed as follows:

$$\widehat{C}_{ij\xi}^{eq,\circ} = \widehat{N}_{ij\xi}^{eq,\circ} \times AUP_{\xi} \quad (16)$$

$$AUP_{\xi} = \sum_{\partial} I_{\xi,\partial} \times \frac{r \times (1+r)^{t_{\xi,\partial}}}{(1+r)^{t_{\xi,\partial}} - 1} \quad (17)$$

$$t_{\partial} = \begin{cases} \min(\text{lifetime of the product, lifetime of the component } \partial) \\ \quad \forall \partial \text{ is a non-reusable component} \\ \max(\text{lifetime of the product, lifetime of the component } \partial) \\ \quad \forall \partial \text{ is a reusable component} \end{cases} \quad (18)$$

where  $\partial$  stands for the component of the cost of a specific piece of equipment (e.g., software, installation, hardware, etc.);  $I_{\xi,\partial}$  is the initial investment for a component  $\partial$  in equipment  $\xi$ , with • standing for  $p, d, f, t$  and  $l$ ;  $r$  is the periodic discount rate; and

$t_{\partial}$  is the amortization period. To determine the appropriate  $t_{\partial}$ , each capital resource is characterized by (1) its life cycle and (2) whether it can be reused on future products. The investment for a reusable resource is annualized over its own lifecycle. Non-reusable resources are annualized over the shorter of the lifecycle of the product and the resource lifecycle. Where a resource consists of several components with different lifetimes or reusability characteristics, the model amortizes each accordingly. In this way, the model provides a high level of resolution and more robust insight into the investment implications of a particular technological or operational strategy. To accommodate the presence of non-dedicated capital, and, therefore, implicitly the existence of other products, capital would need be allocated according to some distributional rule (e.g., production volume or associated revenue).

The final annual equipment cost is thus calculated as:

$$C_i^{equip} = \left( \sum_j \left( \widehat{C}_{ij\xi^*}^{eq,P} + \widehat{C}_{ij\xi^*}^{eq,D} + \widehat{C}_{ij\xi^*}^{eq,F} + \widehat{C}_{ij\xi^*}^{eq,L} \right) + C_i^{eq,T} \right) \times PL \quad (19)$$

The calculation for the final cost for transportation equipment comprehends the implications of stations comprising multiple joining methods. It is calculated as:

$$C_i^{eq,T} = C_{i\xi^{int}}^{eq,T} + C_{i\xi^{mix}}^{eq,T} \quad (20)$$

$$C_{i\xi^{int}}^{eq,T} = \sum_j \left( AUP_{\xi_{ijt}} \times \left[ \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} + \widehat{N}_{ij\xi^*}^{tl,ld} \right] \right) \quad (21)$$

$$C_{i\xi^{mix}}^{eq,T} = \left[ \sum_{\tilde{j}} \left( \widehat{N}_{i\tilde{j}\xi^*}^{tl,wk} + \widehat{N}_{i\tilde{j}\xi^*}^{tl,id} - \left[ \widehat{N}_{i\tilde{j}\xi^*}^{tl,wk} + \widehat{N}_{i\tilde{j}\xi^*}^{tl,id} \right] \right) \right] \times \overline{AUP}_{mix} \quad (22)$$

$\tilde{j} \in \{methods\ with\ equipments\ on\ mixed\ stations\}$

where  $C_{i\xi^{int}}^{eq,T}$  is the cost for transportation equipment used for homogeneous stations;  $C_{i\xi^{mix}}^{eq,T}$  is the transport cost of stations that utilize more than one kind of method;  $\widehat{N}_{ij\xi^*}^{tl,wk}$ ,  $\widehat{N}_{ij\xi^*}^{tl,id}$  and  $\widehat{N}_{ij\xi^*}^{tl,ld}$  are the number of working, idle, and loading stations for Method  $j$  in Group  $i$ ; and  $\overline{AUP}_{mix}$  is the weighted average transport equipment cost for mixed stations, weighted according to the quantity of positioning equipment per method.

#### 4.3.2. Annual cost for tooling

Similar to annual cost for equipment, annual cost for tooling is calculated as:

$$\widehat{C}_{ij\xi}^{tool} = PL \times \left( \widehat{N}_{ij\xi}^{tl,wk} \times I_{ij\xi}^{tl,wk} + \widehat{N}_{ij\xi}^{tl,id} \times I_{ij\xi}^{tl,id} + \widehat{N}_{ij\xi}^{tl,ld} \times I_{ij\xi}^{tl,ld} \right) \times \frac{r \times (1+r)^{t_{product}}}{(1+r)^{t_{product}} - 1} \quad (23)$$

Where  $\widehat{N}_{ij\xi}^{tl,wk}$ ,  $\widehat{N}_{ij\xi}^{tl,id}$  and  $\widehat{N}_{ij\xi}^{tl,ld}$  represent the number of working stations, idle stations and part loading stations, for which the calculation are explained in Section 8.3;  $I_{ij\xi}^{tl,wk}$ ,  $I_{ij\xi}^{tl,id}$  and  $I_{ij\xi}^{tl,ld}$  is the unit price of working stations and idle stations.

Annual final tool cost is calculated as:

$$C_i^{tool} = PL \times \left( N_i^{tl,geo} \times I_i^{tl,geo} + N_i^{tl,res} \times I_i^{tl,res} + N_i^{tl,id} \times I_i^{tl,id} + N_i^{tl,ld} \times I_i^{tl,ld} \right) \times \frac{r \times (1+r)^{t_{product}}}{(1+r)^{t_{product}} - 1} \quad (24)$$

Where  $N_i^{tl,geo}$ ,  $N_i^{tl,res}$ ,  $N_i^{tl,id}$ ,  $N_i^{tl,ld}$  are the number of geo-set stations, respot stations, idle stations and loading stations required by group  $i$ . The section 8.3 will provide details for calculations.

#### 4.3.3. Annual cost for Building

The building investment is estimated from the space needed for an assembly line multiplied by the square footage price. Facilities that supply water, air, and electricity are incorporated into the building investment. The building investment is therefore calculated as:

$$\widehat{C}_{ij\xi}^{building} = PL \times \lambda \times S_i \times \left( \widehat{N}_{ij\xi}^{tl,wk} + \widehat{N}_{ij\xi}^{tl,id} + \widehat{N}_{ij\xi}^{tl,ld} \right) \times I^{building} \times \frac{r \times (1+r)^{t_{plant}}}{(1+r)^{t_{plant}} - 1} \quad (25)$$

Where  $\lambda$  is the coefficient that accounts for scale of spaces needed to operate a subassembly line compared to the space of subassemblies,  $S_i$  is the aggregate area of parts assembled in Group  $i$  and  $I^{building}$  is the unit price of the space.  $t_{plant}$  is the life of a plant.

$$C_i^{building} = PL \times \lambda \times S_i \times \left( N_i^{tl,wk} + N_i^{tl,id} + N_i^{tl,ld} \right) \times I^{building} \times \frac{r \times (1+r)^{t_{plant}}}{(1+r)^{t_{plant}} - 1} \quad (26)$$

Taken together, these equations define a process-based cost model that comprehends the significant direct costs associated with an assembly activity. Furthermore, by basing the estimates of those cost elements on their underlying technological drivers the PBCM is able to effectively differentiate the impacts of variation in architecture, materials, process, and operational context.

## 5. Model application

As with any modeling framework, the usefulness of the above formulation can be more clearly shown through its application. Along those lines, this section will 1) explore the basic function of the PBCM, in particular the manner in which the model presented herein builds up a cost result from technical detail; 2) demonstrate the specific benefits outlined for the PBCM method; and 3) further characterize the interdependency of material, process, and architecture decisions and the contextual sensitivity of these decisions.. This will be accomplished through the use of a specific case study which involves comparing several technology alternatives for assembling the body of a medium sedan.

### 5.1. CASE STUDY PARAMETERS

The case study focuses on two architectural alternatives for a medium –sized sedan: a conventional steel body-frame integral (BFI) structure (a common automotive structural architecture) and an aluminum spaceframe-like architecture (a less common, but occasionally applied alternative). The PBCM presented herein is used to analyze assembly process cost for both design alternatives and to examine the interdependency between product design and process design during the product development process. This particular case was selected because it compactly comprehends these interdependencies. While assembly process cost is important, the authors acknowledge than any real technology evaluation should include other cost components.<sup>7</sup>

Each product design alternative can be realized by various feasible process alternatives. In this analysis, process alternatives are limited to combinations of joining method and automation level. In the interest of presenting a concise, but informative case, both architectural alternatives are modeled using only a single joining method during the whole assembly process. The model presented can accommodate without modification cases with any extent of mixing of joining methods. Two joining

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<sup>7</sup> The analysis here doesn't include cost for part fabrication, which must be evaluated in order to derive the final decision for product design.

methods are considered: RSW (Resistance Spot Welding) and MIG (Metal Inert Gas welding). In this analysis, the steel BFI can be assembled using either joining method while the aluminum space-frame is limited to only MIG. While this is a simplifying assumption, it is representative of the implications of conductivity and geometric limitations on part accessibility associated with the aluminum design. Table 3 and Table 4 summarize these product and process decision options and Table 5 defines the set of scenarios evaluated subsequently by the PBCM.

Details of modeled assumptions for general and operational conditions, factor prices, product description, and process characteristics are provided in Table 6. All data is intended to be representative of conditions within the automotive industry, but do not represent actual data for any firm. Initial values for operating conditions are representative of typical conditions for North American automotive assembly plants. The impact of selected operational conditions is explored subsequently in specific sensitivity analyses.

In Table 7 and Table 8, product and process details are provided only for the steel BFI architecture joined using RSW. The steel BFI assembled using MIG welding was assumed to have identical joining content. The spaceframe design was assumed to require 10% less joining content.

## 5.2. PBCM FUNCTION

Models of cost have always been used in industry to support investment decisions. Activity-based costing (Kaplan 1987 [41]) and other process-based cost research (Graves and Whitney 1979 [25]) (Bloch and Ranganathan 1992 [42]) have significantly extended these methods. These costing approaches, however, are unable to predict the cost-implications of novel technological alternatives. The PBCM method was developed to address this shortcoming and accomplishes this by generating cost projections from details of the underlying physical processes and operations. Figure 3 explores one aspect of that development from technological requirement, through operational resource demand, to the ultimate mapping of economic consequence. The analyses in Figure 3 represent model output on the production of the first group within the BFI case (See Table 7) and show the evolution of key process characteristics and resource requirements that lead up to unit labor cost for that subassembly. Specifically, Figure 3A plots the required joining time for the Motor Compartment Rail. As a processing requirement, joining time derives from the capabilities of the technology and the specifics of the product to be assembled. As such, joining time is independent of the contextual variable, production volume. Despite this independence, as production volume goals increase and available operating time per station decreases, more operational resources are required to accomplish all of the necessary joining. Therefore, joining time directly drives strong volume dependence across capital and labor resource requirements within the model. Figure 3B & C quantifies the evolution of two such modeled resources, namely, assembly equipment and direct laborers. These two quantities develop differently within the model. The notable difference is the discrete progression of stations, whose application is rivalrous, versus the relatively continuous progression of labor requirements that are modeled are fungible across assembly tasks. Finally, once resource requirements are established it is straight forward to map these to cost. In the case of Figure 3D, this mapping is limited to unit labor cost.

All models of assembly cost identified by the authors either implicitly or explicitly assume constant equipment utilization when developing cost estimates. Figure 4 plots the equipment utilization rate ( $U$ ) at different production volumes for the BFI-RSW - Robot scenario, where utilization rate here is calculated as:

$$U = \frac{\sum_i \sum_j TWT_{ij\xi}}{\sum_i \sum_j N_{ij\xi}^{eq,P} \times CT} \quad (27)$$

Clearly, modeled utilization can vary significantly, especially when production volume is low. This behavior is a fundamental feature of organizing processing activities in a serial fashion. As production volumes increase, cycle time,  $CT$ , decreases, but for a range of production volumes, the quantity of required positioning equipment,  $N_{ij\xi}^{eq,P}$ , remains constant. As a result, the equipment utilization rate increases. At high production volumes, the quantities  $N_{ij\xi}^{eq,P}$  and  $CT$ , vary inversely but roughly consistently.

### 5.3. UNDERSTANDING THE BENEFITS OF THE PBCM METHOD

As was detailed previously, by building up cost from technical detail, PBCMs are able to provide unique insights into technological, operational, and strategic decisions. The hypothetical case allows these benefits to be specifically explored.

#### 5.3.1. Identifying Cost Drivers

To better focus technology development efforts it is necessary to understand in detail the drivers of economic performance. Figure 5 shows a percentage breakdown of costs for each of the six technological alternatives at a production volume of 100,000 units per year. Such an analysis provides an initial perspective on the question of underlying cost drivers. Notably each of the technologies shows key differences in the dominant sources of cost. Obviously, the manual methods are driven by labor cost, while fixed costs dominate robotic costs. Ultimately, this type of analysis provides only the information to begin a search for specific cost drivers. The technical detail of the PBCM facilitates this root cause analysis to a fine degree of granularity, but is beyond the scope of this document.

#### 5.3.2. Quantifying necessary process performance hurdles

Because PBCMs build cost up from technological causes, it is possible to use these models to explore the impact of changing technological conditions. Such sensitivity analysis, is useful in exposing the cost drivers described above. However, it is also possible to use this information to quantify what performance is needed from manufacturing in order to bring costs to particular targeted levels. Figure 6 shows an example of such an analysis. As will be described in the next section (see Figure 7A & C), for the Body-Frame Integral architecture, RSW-Manual is modeled to represent the lowest cost technology for low production volumes. However, the MIG-Manual method shows modeled costs only slightly higher than RSW-Manual. An interesting technological development question is what level of performance is required by the MIG method to become economically preferred. Figure 6 shows that answer is specific to a given production volume. Nevertheless, at least up to 50,000 units per year a improvement in MIG speed to 1.4 seconds per join or less would make MIG an economically more attractive option that RSW. As production volumes drop, slower MIG speeds may still allow it to be competitive. If technologists believe that such changes were possible, technology development may be warranted for cost alone.

#### 5.3.3. Quantifying impact of changes in production context

The relative economic position of any set of technologies is not unique, but depends strongly on the strategic and operational context in which they are applied. If developed with sufficient detail and fidelity, cost models can generate invaluable analysis on the impact of such changes. This is particularly useful for early stage strategy decisions, where prospective modes of production are

large and may span not only a range of forms and processes, but also markets and regions. Figure 7 plots the baseline cost projections derived from the model for the six technological alternatives across a range of production volumes. For clarity, the results for the BFI and spaceframe architectures are presented separately. The upper two plots (Figure 7A and C) show the projected unit cost of the BFI and spaceframe alternatives, respectively. The lower plots (Figure 7B and D), plot the same information but relative to one of the alternatives within the set – robotic RSW for the BFI results and robotic MIG for the spaceframe results. The lower plots make it easier to see the specific strategic advantages of a given technology within each set.

Notably, for BFI architecture at baseline conditions, the RSW manual method is modeled to have the lowest costs for volumes below 10,000 units per year. Between 10,000 and around 25,000 units per year, the MIG Robot method is modeled to have the lowest cost. Finally, above around 25,000 units per year, the RSW Method provides the lowest modeled unit cost. By comparison, for the spaceframe architecture the MIG Manual method provides demonstrable lower costs until production volumes just above 10,000 units per year at which point the economies of scale of the MIG Robot method make it preferred.

Although production volume is a key strategic issue, it is not the sole aspect of non-technological context that plays a role in determining cost. One that is particularly pertinent to technology selection decisions is wage<sup>8</sup>. Figure 8 shows the synthesis of the model results when both production volume and wage are considered in this concurrent material – architecture – process case. In this figure, each region represents the sets of conditions under which the model would project that method to have the lowest cost. The hashed region represents conditions under which the model projects that both the Spaceframe MIG-Robot alternative and the BFI RSW-Robot alternative can be assembled at approximately the same cost (less than 5% difference), but that they are notable less expensive than any other technological alternative. Notably, only four technological alternatives are represented in Figure 8. The Steel-BFI-MIG alternatives were not modeled to have lowest cost at any of the conditions investigated.

The over arching trends within Figure 8 are not surprising and match directly to the underlying cost drivers quantified in Figure 5. Namely, the manual methods, with lesser capital investments, are modeled to perform better economically at low wages and low production volumes. Conversely, the higher joining rates of the robotic methods allow them to achieve lower costs as they are able to distribute high investment expenses across a large quantity of products. Nevertheless, the specific location of the transition points among the technologies is not evident without the type of information provided by the model. Finally, Figure 8 makes plain the original claim set forth in this paper, the competitiveness of the materials, architectures, and processes (i.e., joining methods) considered in this case is both strongly sensitive to production context and is wholly interdependent. The former point emerges immediately from the location and shape of the regions in Figure 8. The latter emerges in several observations. Firstly, the absence of RSW-MIG demonstrates that based on model results, the MIG method is only economically competitive when paired in an appropriate

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<sup>8</sup> Wage is one of several location specific aspects of context. Several others including raw materials prices, logistics costs, work schedules, or regional levels of workforce proficiency can also be easily examined within the model presented herein as well as any appropriately sophisticated process-based model.



architecture. Conversely, the competitiveness of the steel BFI architecture can extend beyond the traditional high volume context when coupled with an appropriate manual method.

## 6. SUMMARY

For any real, complex product there are always attributes of performance that are physically oppositional. To accommodate these, designers have at their disposal an ever increasing array of materials, novel product forms, and advanced processes to fashion and join. Each of these can work together to achieve a level of performance that cannot be realized with one technological change alone. The range of available technological options and the interdependence of their impact on performance, means that to tap this technological toolkit, designers cannot rely solely on normative evaluation approaches. Instead, effective decision-making requires tools that can project ultimate product performance. Although sophisticated computational tools that project physical performance have become prevalent, their economic analogs are generally simpler and less robust to technological change.

As this paper has shown, the PBCM method was developed to address this shortcoming and accomplishes this by mapping a description of a product first to technological characteristics of the joining processes then to resource requirements for manufacture and finally to economic consequence (See Figure 3). This technological and operational detail leads to a key difference of the PBCM method compared to other generative cost estimation methods. Namely, the PBCM does not require that capital utilization remains fixed across the range of investigation. While this simplification may be appropriate for certain modes of parallel part manufacture or when strategic scope is limited, it can lead to analytical error for broad assessment of serialized production like found in many assembly operations (See Figure 4).

From an analytical perspective, the PBCM method provides four specific benefits, each of which enables better technological decision making during the product development process. These benefits are: (1) Identifying cost drivers; (2) Quantifying necessary process performance hurdles; (3) Quantifying impact of changes in production context; and (4) Providing a generic platform to discuss cost of process / product developments. Save for the last, each of these was demonstrated in the context of hypothetical, but representative case of material, architecture, and process selection for automobile body assembly. Significantly, each of these was possible even with a limited amount of design information that is available early in the product development process.

The most critical observation that emerges from the presented case analysis is that cost performance of each technological option is strongly interdependent. This point emerges clearly from Figure 8, in which the absence of RSW-MIG demonstrates that, based on model results, the MIG method is only economically competitive when paired in an appropriate material and architecture. Conversely, the competitiveness of the steel BFI architecture can extend beyond the traditional high volume context when coupled with an appropriate manual method.

In the end, product development becomes both more exciting and more challenging as the range of available technological solutions grows. However, to rationally utilize the available palette of technologies, designers require analytical tools that project product performance early in the development process. As this paper has shown, the PBCM is able to fill this early-design need even across complex interdependent design choices that are strongly sensitive to strategic and operational context. Such capability should enable broader application of novel technologies by filling an information void.

## 7. ACKNOWLEDGEMENT

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## 8. APPENDIX

This section will explain how the PCBM projects the required operational resources, which are then converted into financial values to report unit cost, as have been discussed in Section 4.

### 8.1. SCALE OF THE LINE

For use in cost calculations with the MIT-MSL assembly model, there are three key characteristics that define the scale of the line for a given combination of product geometric, assembly requirements, and operational context. These characteristics are 1) the number of parallel lines; 2) the number of pieces of equipment within each parallel line; and 3) the number of stations within each parallel line. (This order of presentation was selected because of it matches with the underlying calculus within the model.) Ultimately, each of these characteristics depends upon a balancing of time – the time needed to do work and the time available to do work. Because of this interrelationship, it will be necessary to interleave within the description of framework for calculating scale the introduction of three core perspectives on time used within the model: 1) cycle time, 2) available station joining time; and 3) required joining time.

#### 1) Cycle Time & Number of Parallel Lines

In MIT-MSL assembly model, cycle time ( $CT$ ) is defined as the pace at which the assembly line operates. During operating hours, when functioning, the line produces one finished assembly every  $CT$ . Nominally, cycle time is simply defined as a balance of available time and desired production rate. This quantity will be labeled  $CT_o$  and is computed as:

$$CT_o = \frac{3600 \times AOT \times D}{V} \quad (28)$$

where  $AOT$  refers to the available operating time for the facility, as illustrated in Figure 1 and calculated as:

$$AOT = (H_{shift} - H_{unpdbk} - H_{pdbk} - H_{updt}) \times Sft + H_{OT} \quad (29)$$

where  $H_{pdbk}$  is the paid break time in hours per shift and  $H_{updt}$  is the unpaid downtime in hours per shift.

Conceptually, based on Equation (28), the cycle time of the line can shrink without bound as production targets ( $V$ ) increase. In reality, cycle time is limited by two requirements. First, some

joining processes are discrete in nature and cannot be subdivided beyond some atomic unit. Additionally, on a more practical level, during each cycle, certain activities (loading, unloading, transfers, etc.) must occur to ready parts and equipment for their respective assembly operations. In either case, cycle time cannot drop below the time required to accomplish station preparation and at least one unit of joining. However, long before this fundamental is reached short cycles times begin to demand inefficient lines, dominated by the non-value added tasks of preparation, not joining. To avoid this inefficiency, it is necessary to specify a minimum station cycle time,  $CT_{min}$ , below which operation is precluded. To ensure that any given production target can still be met, it is necessary to allow for the occurrence of parallel assembly operations. The number of parallel lines,  $PL$ , can be calculated as:

$$PL = \left\lceil \frac{CT_{min}}{CT_o} \right\rceil \quad (30)$$

Assuming that all parallel lines are configured identically, the actual cycle time can be computed as:

$$CT = \frac{3600 \times AOT \times D}{V / \left\lceil \frac{CT_{min}}{CT_o} \right\rceil} = CT_o \times PL \quad (31)$$

Although the model as presented does not comprehend yield loss, variance from this can be accounted for by tracking volume and, therefore, cycle time differentially by group. Other costs will scale accordingly based on these quantities.

## 2) Available Station Joining Time (ASJT)

Because some activities must happen to ready parts and equipments, the actual time available for joining, denoted as ASJT, is less than the actual cycle time and is calculated as follows:

$$ASJT = CT - T_{tran} - T_{c/uc} \quad (32)$$

Where  $T_{tran}$  is the transportation time to transfer assembled parts between stations and  $T_{c/uc}$  is the time for a fixture to clamp and unclamp parts before joining work begins.

## 3) Total Working Time (TWT):

The total working time ( $TWT$ ) is the time for a given set of parts or sub-assemblies to be joined together by a specified type of equipment using one joining method were there only one piece of joining equipment available.

Within the MIT-MSL assembly model, joining processes are classified into three types (see Figure 2) according to the manner that joints are completed: 1) continuous, 2) semi-continuous, and 3) discrete. For a continuous process, the equipment completes the joining task by moving along the surface of parts without any interruption. A semi-continuous process is one where joining equipment needs to continually move along the surface of parts to finish a single joint allowing only for brief minor path interruptions. The application of adhesives at multiple locations on a single part is one

example of this category of process. Discrete processes are those where each join is individually distinct and, generally, of consistent, non-variable dimensions.

As shown in Equation (33), the required joining time ( $RJT$ ) for a semi-continuous process (or a continuous process represented as have only one join) depends on four quantities: the average length  $\overline{L}_{ij}$  per join, the number of joins  $n_{ij}$ , joining rate  $\mu_{j\xi_d}$  determined by dispensing equipment, and the moving time  $IT_{j\xi_p}$  that the positioning equipment requires from one join to the next. For a discrete process,  $RJT$  is normally determined by the joining time per join  $JT_{j\xi_d}$ , the inter-moving time  $IT_{j\xi_p}$ , and the number of required total joins  $n_{ij}$ .

$$RJT_{ij\xi} = \begin{cases} JT_{j\xi_d} \times n_{ij} + IT_{j\xi_p} \times (n_{ij} - 1) & \forall j \text{ is discrete} \\ \frac{\overline{L}_{ij}}{\mu_{j\xi_d}} \times n_{ij} + IT_{j\xi_p} \times (n_{ij} - 1) & \forall j \text{ is semi-continuous} \end{cases} \quad (33)$$

Considering the loss due to small scale run time variation and to accommodate future product design changes, the total working time of joining for Method  $j$  in Group  $i$  in seconds,  $TWT_{ij\xi}$  is calculated as:

$$TWT_{ij\xi} = \frac{RJT_{ij\xi}}{\rho_j} \quad (34)$$

where  $\rho_j$  is the equipment loading factor for Method  $j$ .

## 8.2. REQUIRED EQUIPMENT

### 1) Positioning Equipment

Since  $TWT_{ij\xi}$  is the time required to finish a joining task if there is only one piece of equipment available and  $ASJT$  is the time available for joining, the number of pieces of positioning equipment needed is calculated as:

$$\widehat{N}_{ij\xi}^{eq,P} = \frac{TWT_{ij\xi}}{ASJT - 2 \times SFT_{ij\xi_p}} \quad (35)$$

Where  $SFT_{\xi_p}$  is the time needed for the positioning equipment to travel to the home position and to return from the final join. Equation (35) can be modified easily to accommodate a parallel approach to meeting production volume targets. Specifically, the quantity  $2 \times SFT_{ij\xi_p}$  should be moved from a decrement in the denominator to an increment in the numerator.

$$N_{ij\xi}^{eq,P} = \left\lceil \widehat{N}_{ij\xi}^{eq,P} \right\rceil \quad (36)$$

## 2) Joining Equipment

Assuming a given single piece of joining equipment requires one piece of positioning equipment to move, the total number of pieces of joining equipment is equal to the number of pieces of positioning equipment, such that:

$$\widehat{N}_{ij\xi}^{eq,D} = \widehat{N}_{ij\xi}^{eq,P} \quad (37)$$

$$N_{ij\xi}^{eq,D} = N_{ij\xi}^{eq,P} \quad (38)$$

## 3) Material Feeding Equipment

Material feeding equipment can either be dedicated in one group or shared across groups. When it is shared across groups, the model distributes the cost of this equipment according to the percentage of consumables for each joining process over the total capacity of the material feeding equipment. Thus, the number of material feeding equipment is given by:

$$\widehat{N}_{ij\xi}^{eq,F} = \begin{cases} \left[ \frac{Cap_{ij\xi_f}}{TC_{\xi_f}} \right] & \forall f \text{ is dedicated} \\ \frac{Cap_{ij\xi_f}}{TC_{\xi_f}} & \forall f \text{ is shared across groups} \end{cases} \quad (39)$$

Where  $Cap_{ij\xi_f}$  is the required capacity of the material feeding equipment supplying consumed materials for the Method  $j$  in Group  $i$ .  $TC_{\xi_f}$  is the total capacity of the material feeding equipment.

$$N_{ij\xi}^{eq,F} = \widehat{N}_{ij\xi}^{eq,F} \quad (40)$$

## 4) Loading Equipment

The model assumes one piece of loading equipment exists per loading station. Since loading is modeled as a group level activity, for the purposes of selecting the preferred technological instance, the number of loading equipment for each instances is equal to the number of loading stations required by the respective group. For computing final costs, the number of pieces of loading equipment equals the number of loading stations required by the group. Therefore, the number of pieces of loading equipment is given by:

$$\widehat{N}_{ij\xi}^{eq,L} = \widehat{N}_{i\xi}^{ul,L} \quad (41)$$

$$N_{i\xi}^{eq,L} = N_{i\xi}^{ul,L} \quad (42)$$

## 5) Transportation Equipment

For the purposes of selecting the preferred instance, the number of pieces of transportation equipment for Method  $j$  in Group  $i$  is equal to the number of stations in a group.

$$\widehat{N}_{ij\xi}^{eq,T} = \widehat{N}_{ij\xi}^{tl,wk} + \widehat{N}_{ij\xi}^{tl,id} + \widehat{N}_{ij\xi}^{tl,ld} \quad (43)$$

The quantity of required transport equipment is not calculated explicitly within the model. Interested readers can infer this figure from the calculation of transport cost, Equations (21) and (22).

### 8.3. REQUIRED TOOL

In the context of the MIT-MSL assembly model, tool refers to specialized devices which are used to locate, clamp, or support individual parts or subassemblies to be joined together during an assembly process. By definition, tools are hardware dedicated to the production of only one product. Tool investment is a function of size, complexity, precision, and flexibility requirements. The tool strategy also plays an important factor in determining cost. Various tool strategies are used in industries. In the MIT-MSL model comprehends one strategy for primary joining tools that divides assembly into two stages. The first stage creates those joins required to fix the geometry of the assembled parts -- Geometric Setting or “Geoset” for short. In the second stage, additional joins are created to meet structural requirements of the assembly. Stations which predominantly process such joints are known as “Respot” stations. Because of the strict geometric tolerances, geoset tools will generally be more expensive than equivalent respot tools

In addition, there are two further categories of tools, idle and loading , for which definitions are included in Table 2. These tools require even less positioning accuracy since they are not involved in actual joining operations and, therefore, are the least expensive.

The following describes the developed algorithm to calculate the required quantity of assembly stations and the corresponding number of tools that populate those stations:

#### 1) Primary Joining Stations and Tools

After calculating the required quantity of positioning equipment, the MIT-MSL PBCM calculates the required number of geoset and respot stations and the corresponding tools. This quantity is determined by the geometric requirements of the specific positioning equipment and the space subtended by each group, according to:

$$\widehat{N}_{ij\xi}^{tl,wk} = \frac{\left[ \widehat{N}_{ij\xi}^{eq,P} \right]}{\left[ \nu \times S_i / S_{ij\xi_p} \right]} \quad (44)$$

where  $wk$  is the type of active station, which can be geoset or respot;  $S_{ij\xi_p}$  is the area required by positioning equipment  $\xi_p$ ; and  $\nu$  is a scalar ratio between the subassembly size and the station's size.

Since generally  $\widehat{N}_{ij\xi}^{tl,wk}$  is not an integer, if this quantity is used unmodified, the model would represent a production strategy where some number of stations would be only fractionally utilized. To capture a more efficient use of space, capital, and time, fractional stations for different methods within a group are combined within the model. Stations that require any quantity of geoset joining are

modeled as a geoset station. If  $\widehat{N}_{ij\xi}^{tl,geo}$  denotes the number of stations if  $j$  is a geoset method and  $\widehat{N}_{ij\xi}^{tl,res}$  if  $j$  is a respot method, then the final number of geoset stations and tools  $N_{ij\xi}^{tl,geo}$  and the final number of respot stations/tools  $N_{ij\xi}^{tl,res}$  are calculated as:

$$N_i^{tl,geo} = \sum_j \left[ \widehat{N}_{ij\xi^*}^{tl,geo} \right] + \left[ \sum_j \sigma_{ij}^{geo} \right] + \left[ \phi_i^{geo} \right] \quad (45)$$

$$N_i^{tl,res} = \sum_j \left[ \widehat{N}_{ij\xi^*}^{tl,res} \right] + \left[ \sum_j \delta_{ij}^{res} \right] + \left[ \phi_i^{geo} + \phi_i^{res} \right] - \left[ \phi_i^{geo} \right] \quad (46)$$

Where

$$\sigma_{ij}^{geo} = N_{ij\xi^*}^{tl,geo} - \left[ N_{ij\xi^*}^{tl,geo} \right] \quad (47)$$

$$\delta_{ij}^{res} = N_{ij\xi^*}^{tl,res} - \left[ N_{ij\xi^*}^{tl,res} \right] \quad (48)$$

$$\phi_i^{geo} = \sum_j \sigma_{ij}^{geo} - \left[ \sum_j \sigma_{ij}^{geo} \right] \quad (49)$$

$$\phi_i^{res} = \sum_j \delta_{ij}^{res} - \left[ \sum_j \delta_{ij}^{res} \right] \quad (50)$$

## 2) Idle Stations and Tools

The number of idle stations is modeled as proportional to number of active stations required by a given method:

$$\widehat{N}_{ij\xi}^{tl,id} = \theta_j \times \widehat{N}_{ij\xi}^{tl,wk} \quad (51)$$

$$N_{ij\xi}^{tl,id} = \theta_j \times N_{ij\xi}^{tl,wk} \quad (52)$$

$\theta_j$  is the ratio of idle stations to active stations for Method  $j$ .

## 3) Loading Stations and Tools

Since loading activity only happens at the group level, the number of loading stations used for selection of the preferred instance for methods is equal to the number of loading stations in the group:

$$\widehat{N}_{ij\xi}^{tl,ld} = \widehat{N}_{i\xi}^{tl,ld} \quad (53)$$

The number of loading stations required by a group is based on the amount of time required to load the parts that comprise that group and the amount of time available within partially utilized joining stations. When time available within fractionally utilized joining stations is insufficient to meet loading requirements, dedicated loading stations are added within the model. Therefore, the number of part loading tool is calculated as:

$$\widehat{N}_{i\xi}^{tl,ld} = MAX\left(\left[\frac{m_i \times LT}{ASJT} - \tau\right], 0\right) \quad (54)$$

$$\tau = \left[\phi_i^{geo} + \phi_i^{res}\right] - (\phi_i^{geo} + \phi_i^{res}) \quad (55)$$

where  $m_i$  is the number of parts that need to be loaded to the group  $i$  and  $LT$  is the average loading time for each part.

Final number of part loading tool is simply:

$$N_{i\xi}^{tl,ld} = \widehat{N}_{i\xi}^{tl,ld} \quad (56)$$

#### 8.4. REQUIRED ENERGY CONSUMPTION

The calculations of energy consumption of equipment are conducted as follows:

$$\widehat{EN}_{ij\xi}^P = (TW_{ij\xi} + 2 \times SFT_{\xi_p}) \times PW_{\xi_p} / 3600 \quad (57)$$

$$\widehat{EN}_{ij\xi}^D = \begin{cases} n_{ij} \times PW_{\xi_d} & \forall j \text{ is discrete} \\ TW_{ij\xi} \times PW_{\xi_d} / 3600 & \forall j \text{ is semi-continuous} \end{cases} \quad (58)$$

$$\widehat{EN}_{ij\xi}^F = \begin{cases} n_{ij} \times PW_{\xi_f} & \forall j \text{ is discrete} \\ TW_{ij\xi} \times PW_{\xi_f} / 3600 & \forall j \text{ is semi-continuous} \end{cases} \quad (59)$$

$$\widehat{EN}_{ij\xi}^T = PW_{\xi_t} \times \left( \widehat{N}_{ij\xi}^{tl,wk} + \widehat{N}_{ij\xi}^{tl,id} \right) \quad (60)$$

$$\widehat{EN}_{ij\xi}^L = PW_{\xi_l} \times \widehat{N}_{ij\xi}^{tl,ld} \quad (61)$$

Among the equations above, the  $PW_{\xi_s}$  s, are the power requirements for the equipment types that comprise  $\xi$ . For a discrete process, power required and time needed to make a join are determined by technological requirement. Therefore, energy consumption per join is available as industrial data. For semi-continuous processes, the energy consumption per join also depends on the time needed to finish the join. As such, energy consumption is calculated based on the total working time in seconds and the power consumption.

Energy consumption used for computing final cost is modeled using the equations above based on the characteristics of  $\xi^*$  except for transportation equipment, paralleling the approach to calculate the final cost of transportation equipment. As such final energy requirements is calculated as:

$$EN_i^T = EN_{i\xi^{mnt}}^T + EN_{i\xi^{mix}}^T \quad (62)$$

$$EN_{i\xi^{mnt}}^T = \sum_j \left( PW_{\xi_{jt}} \times \left[ \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} + \widehat{N}_{ij\xi^*}^{tl,ld} \right] \right) \quad (63)$$

$$EN_{i\xi^{mix}}^T = \left[ \sum_j \left( \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} - \left[ \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} \right] \right) \right] \times \overline{PW}_{mix} \quad (64)$$



Where  $\overline{PW}_{mix}$  is the weighted average of the energy required by transportation equipment for stations that contain multiple methods.

## 8.5. REQUIRED DIRECT LABOR

The number of direct laborers allocated to method  $j$  within group  $i$  used in technology selection,  $\widehat{N}_{ij\xi}^{lb}$ , is calculated as:

$$\widehat{N}_{ij\xi}^{lb} = (1 + \omega_r + \omega_q + \omega_f + \omega_t + \omega_a) \times \widehat{N}_{ij\xi}^{lb,assm} \quad (65)$$

Where  $\omega_r$ ,  $\omega_q$ ,  $\omega_f$ ,  $\omega_t$  and  $\omega_a$  are ratios of the number of rework workers, quality workers, finish workers, team leaders, and absentee workers to the number of assembly workers,  $\widehat{N}_{ij\xi}^{lb,assm}$ , (e.g.,  $\omega_r = \frac{N_r}{N_{assm}}$ ).  $\widehat{N}_{ij\xi}^{lb,assm}$  represents the number of workers required by various types of equipment, so it is calculated as:

$$\widehat{N}_{ij\xi}^{lb,assm} = LI_{\xi_p} \times \widehat{N}_{ij\xi}^{eq,P} + LI_{\xi_f} \times \widehat{N}_{ij\xi}^{eq,F} + LI_{\xi_t} \times \widehat{N}_{ij\xi}^{eq,T} + LI_{\xi_l} \times \widehat{N}_{ij\xi}^{eq,L} \quad (66)$$

$LI_{\xi}$  labor intensity for various equipment, reflects the level of automation of the equipment.

The final labor calculation is calculated as:

$$\begin{aligned} N_{ij\xi}^{lb} &= (1 + \omega_r + \omega_q + \omega_f + \omega_t + \omega_a) \times N_i^{lb,assm} \\ N_i^{lb,assm} &= \sum_j \left( LI_{\xi_p} \times \widehat{N}_{ij\xi^*}^{eq,P} + LI_{\xi_d} \times \widehat{N}_{ij\xi^*}^{eq,D} + LI_{\xi_f} \times \widehat{N}_{ij\xi^*}^{eq,F} \right) + N_i^{lb,T} + N_i^{lb,L} \end{aligned} \quad (67)$$

Paralleling the calculation of energy consumption for final transportation, labor for transportation equipment also is calculated in a weighted average approach:

$$N_i^{lb,T} = N_{i\xi^{int}}^{lb,T} + N_{i\xi^{mix}}^{lb,T} \quad (68)$$

$$N_{i\xi^{int}}^{lb,T} = \sum_j \left( LI_{\xi_{ijt}} \times \left[ \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} + \widehat{N}_{ij\xi^*}^{tl,ld} \right] \right) \quad (69)$$

$$N_{i\xi^{mix}}^{lb,T} = \left[ \sum_j \left( \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} - \left[ \widehat{N}_{ij\xi^*}^{tl,wk} + \widehat{N}_{ij\xi^*}^{tl,id} \right] \right) \right] \times \overline{LI}_{mix} \quad (70)$$

Where  $\overline{LI}_{mix}$  is the weighted average of the number of laborers required by transportation equipment for for stations that contain multiple methods.

Lastly, the number of laborers needed for loading parts into group  $j$ ,  $N_i^{lb,L}$ , is calculated according to Equations (71) to (73).

$$N_i^{lb,L} = \left[ \max \left( \frac{LT \times m_i}{ASJT} - \min(availLabor_i, availEquip_i), 0 \right) \right] \quad (71)$$

$$availLabor_i = \left[ \sum_j \widehat{N}_{ij\xi^*}^{eq,P} \times LI_{\xi_P} \right] - \sum_j \widehat{N}_{ij\xi^*}^{eq,P} \times LI_{\xi_P} \quad (72)$$

$$availEquip_i = 1 - \sum_j \left[ \widehat{N}_{ij\xi^*}^{eq,P} - PK_{ij} \times \left[ \frac{\widehat{N}_{ij\xi^*}^{eq,P}}{PK_{ij}} \right] \right] \quad (73)$$

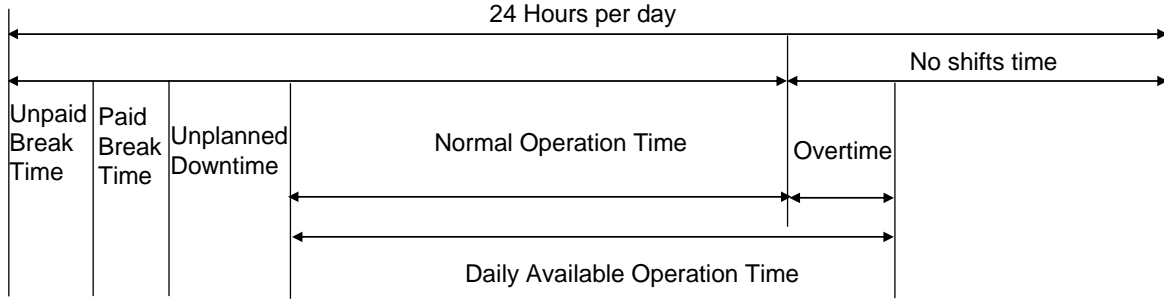
Where  $availLabor_i$  accounts for the available loading time from laborers primarily assigned to man positioning equipment and  $availEquip_i$  accounts for the time available within primary loading stations that can be allocated to loading.

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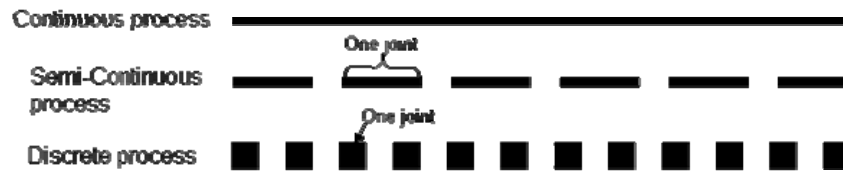
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## 10. FIGURES



**Figure 1** A schematic description of the operating time characteristics comprehended within the model for 24 hours of plant operation



**Figure 2** Representation of different joining processes

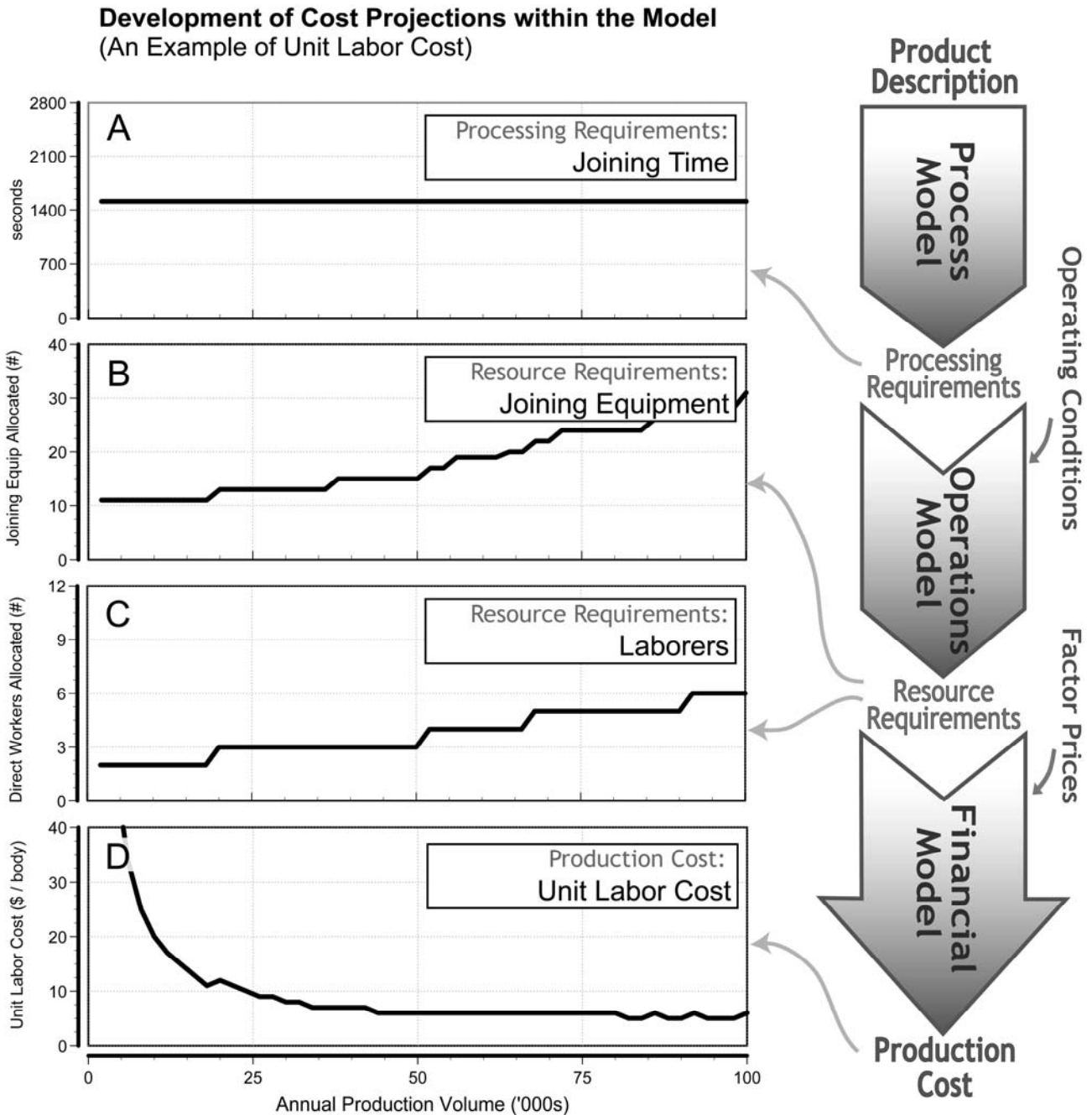


Figure 3. The development of intermediate and final outcomes within the PBCM. This example highlights key determinants of unit labor cost.

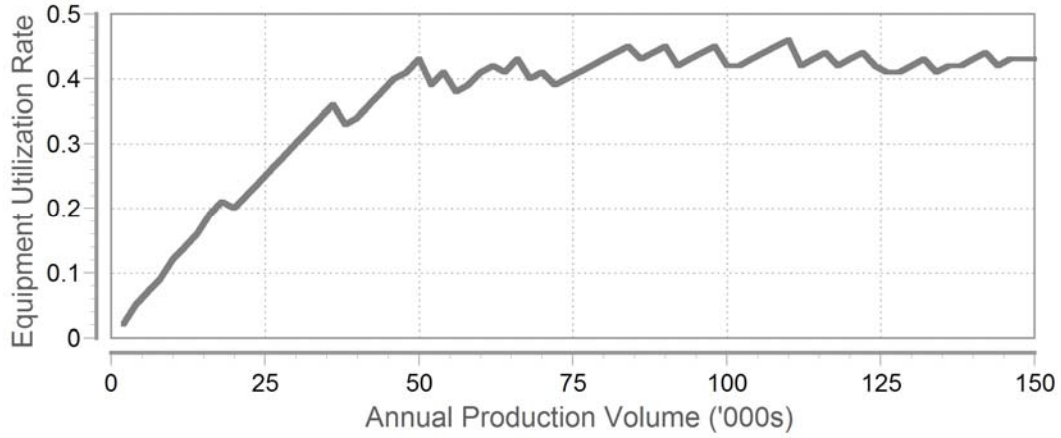


Figure 4 The impact of production volume on the utilization of equipment for the body frame integral architecture assembled using resistance spot welding. Results are representative of other technologies.

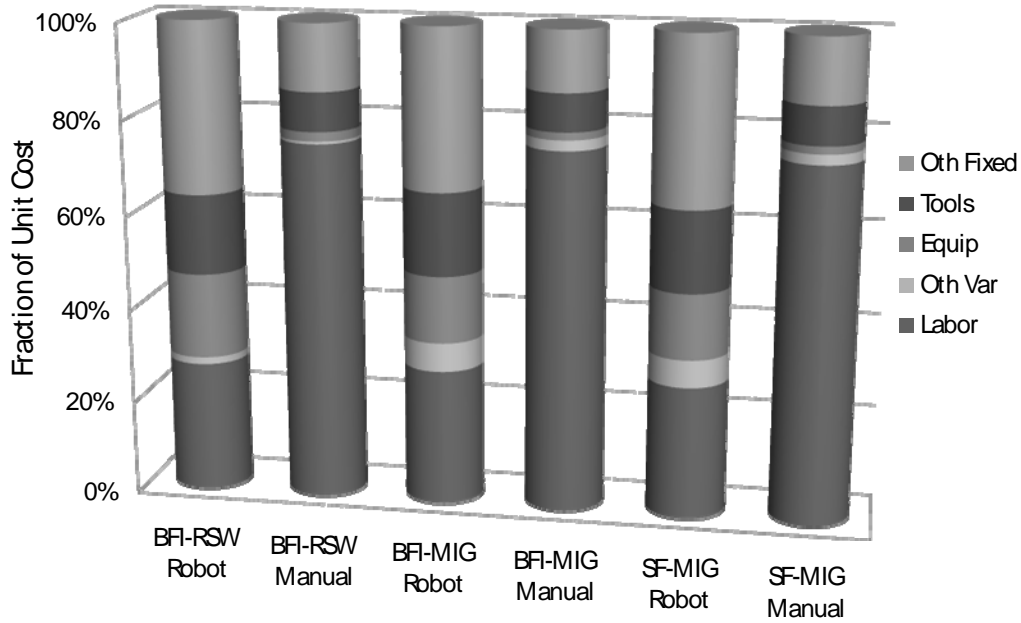


Figure 5. Cost breakdown by element of the six technological options at a production volume of 100,000 units per year.

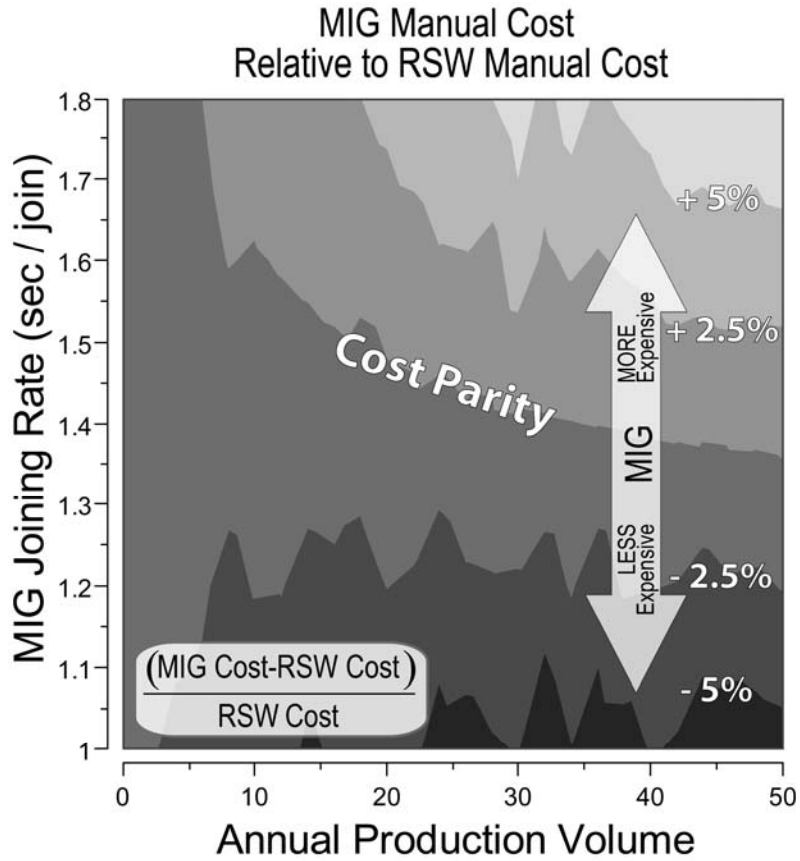
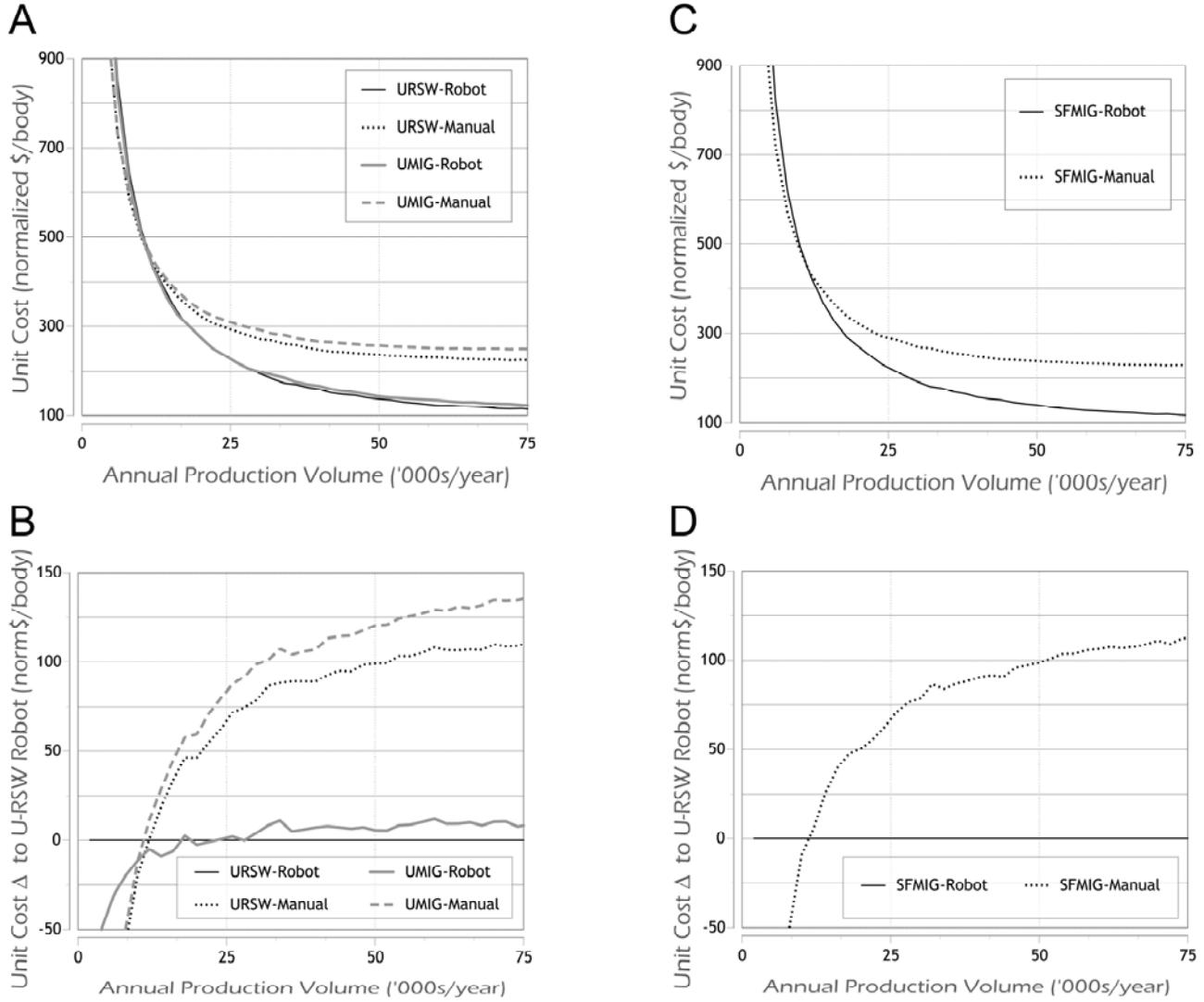


Figure 6. Relative cost of Body-frame integral cost using MIG Manual vs. RSW Manual





**Figure 7. Baseline modeled cost projections for the six technology alternatives. (A&C) plot absolute unit cost. (B&D) plot the difference between absolute cost of the technology relative to a baseline. Baseline: RSW-Robot for Unibody technologies; MIG\_Robot for spaceframe technologies.**

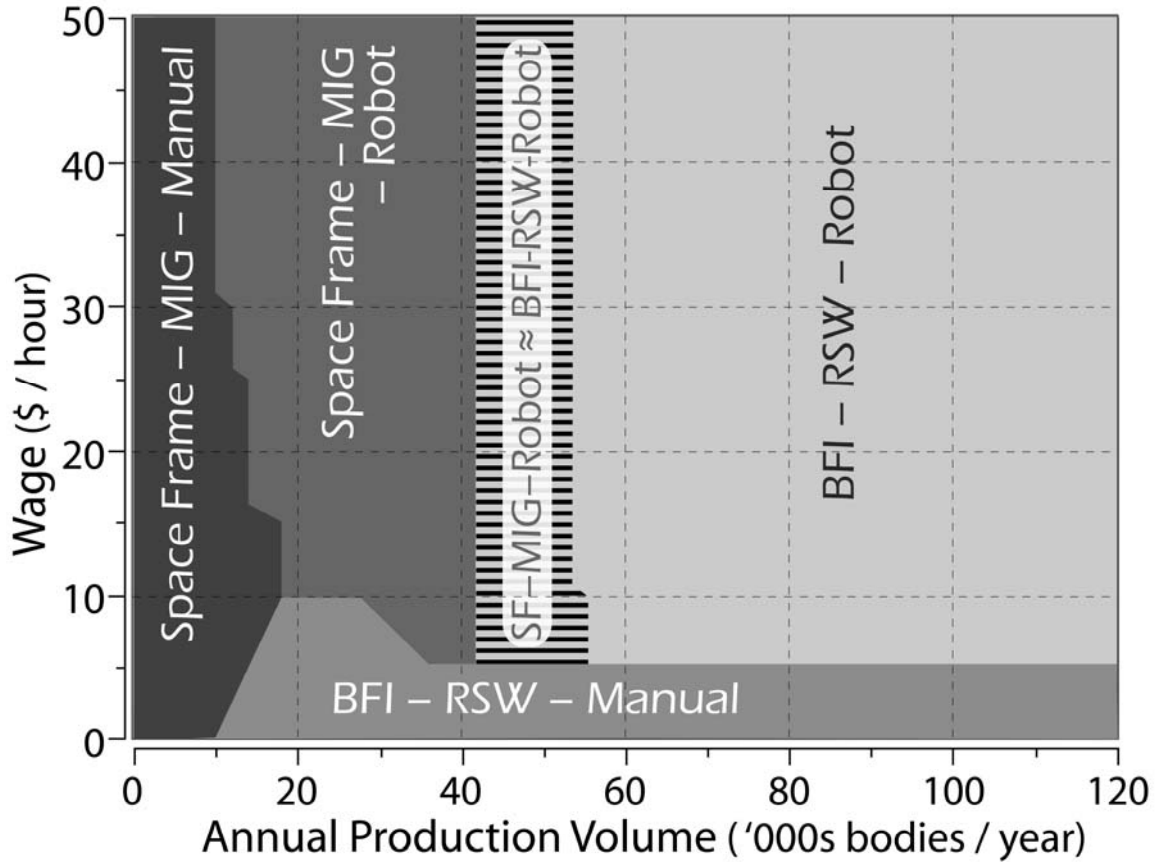


Figure 8. Map of regions of lowest modeled cost for the technological alternatives considered within the case across a range of annual production volumes and labor wages. Hashed region represents conditions under which Spaceframe-MIG-Robot and BFI-RSW-Robot are approximately equivalent in cost, but lower than other alternatives. The BFI-MIG alternatives are not modeled to have the lowest cost at any of the conditions modeled.

## 11. TABLES

Table 1 Categories and definitions of equipments in an assembly process

Category	Definition	Set denotation	instances
Positioning Equipment	Move joining equipment from one joint location to the next.	$\mathcal{P}$	Robot, manual
Dispensing Equipment	Dispensing chemicals onto parts or welding distinct parts using mechanical mechanism.	$\mathcal{D}$	Adhesive gun
Material Feeding Equipment	Store and supply consumable materials such as adhesives, bolts, electrodes needed to join parts.	$\mathcal{F}$	Adhesive pump system
Transportation Equipment	Transfer parts or sub-assembled parts from	$\mathcal{T}$	Skid system, Pallet, conveyor

	station to station.		
Loading Equipment	Load parts onto tool so that joining equipment can work upon parts.	$\mathcal{L}$	Manual, robot

**Table 2 Categories and definitions of tool in assembly process**

	Category	Definition
A	Geoset tool	Tool on which joints setting the geometry of the assembled parts are processed
B	Respot tool	Tool on which joints serving to strengthen the structural strength and rigidity of the assembly are processed
C	Idle tool	Tool on which parts or subassemblies are placed as a buffer between stations
D	Loading tool	Tool on which parts that are to be loaded to assembling process are placed.

**Table 3 Differences between unibody architecture and spaceframe architecture**

Architecture	Material	Subassembly Count	Joining Method	Joining Intensity
Unibody	Steel	39	RSW/MIG	4459 welds/stitches
Spaceframe	Aluminum	39	MIG	4013 stitch <sup>9</sup>

**Table 4 Difference between different assembly processes**

Joining Method	Average Joining Rate per joint		Labor Requirements per Weld Gun		Average Investment per Weld Gun	
	Manual	Robotic	Manual	Robotic	Manual	Robotic
RSW	4.5s	3s	1	0.15	\$6000	\$110000
MIG	3.8s	3.5s	1	0.15	\$3000	\$88000

**Table 5 Alternatives that are evaluated by PBCM**

Product Alternatives		Process Alternatives		Scenario
Architecture	Material	Joining method	Automation Level	
Unibody	Steel	RSW	Robotic	1
		RSW	Manual	2
		MIG	Robotic	3
		MIG	Manual	4
SpaceFrame	Aluminum	MIG	Robotic	5
		MIG	Manual	6

**Table 6 Operation Conditions**

Parameters	symbol	value	unit
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<sup>9</sup> 1 Stitch equals approximately 2.5 cm.

Days per Year	$D$	235	days/yr
Wage for normal operating time (including benefits)	$Wage_{normal}$	25	\$/hr
Wage for overtime (including benefits)	$Wage_{OT}$	25	\$/hr
Interest rate	$r$	10%	
Labor Inputs			
Rework worker per assembly worker	$\omega_r$	0.2	
Quality worker per assembly worker	$\omega_q$	0.0025	
Finish Workers per assembly worker	$\omega_f$	0.003	
Team Leaders per assembly worker	$\omega_t$	0.15	
Absentee per assembly worker	$\omega_a$	0.11	
Maintenance worker per assembly Worker	$\omega_{mtn}$	0.1	
Group manager per assembly Group	$\omega_{gm}$	1	
Building space factor			
Building space factor	$\lambda$	2	
Building Unit Cost	$\rho_{building}$	1200	\$/sqm
Production Life	$t_{product}$	5	yrs
Building Life	$t_{plant}$	40	yrs
Downtimes:			
Number of Shifts	$Sft$	2	shifts
Shift Characteristics			
Shift Duration	$H_{shift}$	8	hrs/shift
Overtime duration	$H_{OT}$	0	Hrs/day
Worker unpaid breaks	$H_{updbk}$	0	hrs/shift
Worker paid breaks	$H_{pdbk}$	0.6	hrs/shift
Unplanned downtime	$H_{updt}$	0.5	hrs/shift

Table 7 Product Information

Group ID	# of Discrete Parts #	Group Size m <sup>2</sup>
No.1	4	3
No.2	17	3
No.3	16	3

No.4	4	3
No.5	5	3
No.6	4	3
No.7	10	3
No.8	3	3
No.9	3	3
No.10	4	3
No.11	2	3
No.12	8	3
No.13	4	3
No.14	12	3
No.15	14	3
No.16	4	3
No.17	12	3
No.18	3	3
No.19	3	3
No.20	4	3
No.21	3	3
No.22	5	3
No.23	5	3
No.24	3	3
No.25	3	3
No.26	3	3
No.27	3	3
No.28	3	3
No.29	3	3
No.30	6	3
No.31	8	3
No.32	21	3
No.33	21	3
No.34	10	3
No.35	9	3
No.36	9	3
No.37	8	3
No.38	5	3
No.39	9	3

**Table 8 Process Information**

Group ID #	Method ID #	Tool type	# of joinings
No.1	RSW - Steel	G	38
No.1	RSW - Steel	G	22
No.1	RSW - Steel	G	5
No.2	RSW - Steel	G	133
No.2	RSW - Steel	G	48
No.2	RSW - Steel	G	35
No.2	RSW - Steel	G	1
No.3	RSW - Steel	G	133
No.3	RSW - Steel	G	48
No.3	RSW - Steel	G	35
No.3	RSW - Steel	G	7
No.4	RSW - Steel	G	20
No.4	RSW - Steel	G	16
No.5	RSW - Steel	G	21
No.5	RSW - Steel	G	31
No.6	RSW - Steel	G	18
No.6	RSW - Steel	G	31
No.7	RSW - Steel	G	39
No.7	RSW - Steel	G	23
No.7	RSW - Steel	G	7
No.7	RSW - Steel	G	7
No.7	RSW - Steel	G	3
No.8	RSW - Steel	G	5
No.8	RSW - Steel	G	9
No.8	RSW - Steel	G	3
No.8	RSW - Steel	G	4
No.8	RSW - Steel	G	4
No.9	RSW - Steel	G	5
No.9	RSW - Steel	G	9
No.9	RSW - Steel	G	3
No.9	RSW - Steel	G	8
No.9	RSW - Steel	G	4
No.10	RSW - Steel	G	36
No.10	RSW - Steel	G	31
No.10	RSW - Steel	G	5

No.11	RSW - Steel	G	10
No.11	RSW - Steel	G	9
No.11	RSW - Steel	G	4
No.11	RSW - Steel	G	9
No.12	RSW - Steel	G	149
No.13	RSW - Steel	G	221
No.13	RSW - Steel	G	55
No.13	RSW - Steel	G	13
No.13	RSW - Steel	G	21
No.14	RSW - Steel	G	42
No.14	RSW - Steel	G	1
No.14	RSW - Steel	G	72
No.15	RSW - Steel	G	42
No.15	RSW - Steel	G	72
No.16	RSW - Steel	G	26
No.16	RSW - Steel	G	31
No.17	RSW - Steel	G	198
No.17	RSW - Steel	G	51
No.17	RSW - Steel	G	88
No.18	RSW - Steel	G	8
No.18	RSW - Steel	G	-
No.19	RSW - Steel	G	10
No.19	RSW - Steel	G	3
No.20	RSW - Steel	G	5
No.21	RSW - Steel	G	8
No.22	RSW - Steel	G	23
No.22	RSW - Steel	G	3
No.23	RSW - Steel	G	21
No.23	RSW - Steel	G	3
No.24	RSW - Steel	G	10
No.25	RSW - Steel	G	12
No.25	RSW - Steel	G	8
No.26	RSW - Steel	G	8
No.27	RSW - Steel	G	8
No.28	RSW - Steel	G	8
No.28	RSW - Steel	G	8

No.28	RSW - Steel	G	-
No.29	RSW - Steel	G	8
No.29	RSW - Steel	G	8
No.29	RSW - Steel	G	-
No.30	RSW - Steel	G	18
No.30	RSW - Steel	G	29
No.31	RSW - Steel	G	577
No.31	RSW - Steel	G	73
No.32	RSW - Steel	G	42
No.32	RSW - Steel	G	56
No.33	RSW - Steel	G	42
No.33	RSW - Steel	G	56
No.34	RSW - Steel	G	35
No.34	RSW - Steel	G	39
No.35	RSW - Steel	G	35
No.35	RSW - Steel	G	39
No.36	RSW - Steel	G	278
No.36	RSW - Steel	G	65
No.36	RSW - Steel	G	20
No.37	RSW - Steel	G	692
No.37	RSW - Steel	G	65
No.37	RSW - Steel	G	1
No.37	RSW - Steel	G	33
No.38	RSW - Steel	G	59
No.38	RSW - Steel	G	23
No.39	RSW - Steel	G	38
No.39	RSW - Steel	G	29