

Development of an Optimal Manufacturing Strategy for Low-Volume Specialty Vehicles

By
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B.S. Applied Physics, State University of New York at Binghamton, 1993

Submitted to the Sloan School of Management
and the Department of Mechanical Engineering
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and
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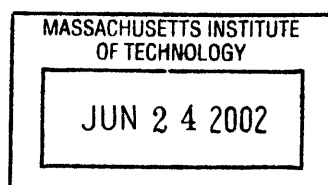
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ABSTRACT

In recent years, the automotive industry has found it necessary to adjust its offerings to consumer desires that change more rapidly and are more varied than in the past. This factor, combined with an increase in worldwide competition, is requiring automotive companies to move faster in developing and producing new vehicles, and to be profitable at lower volumes per model. To address these issues, General Motors recently initiated the Halo program to quickly bring highly desirable show cars with innovative design concepts into production. The first of these vehicles is the Chevrolet Super Sports Roadster (SSR), a retro styled sport truck with a fully automatic retractable roof. The Halo Program calls for a unique new vehicle such as the SSR to be launched at regular intervals, up to a steady-state condition of multiple different Halo vehicles in production simultaneously. To maintain the strong appeal and high exclusivity of these vehicles, production volumes are limited to approximately 10,000 of each Halo model per year. In order to meet the business case for these highly differentiated low-volume Halo vehicles, the manufacturing plan requires that GM implement a *batch build* production strategy.

This thesis develops a batch build manufacturing strategy for the Halo vehicles based on overall program cost, material, labor and equipment changeover constraints. In addition to analyzing and developing the batch build factory changeover process, a mathematical linear program optimization model is created to optimize the lot size and changeover frequency of each Halo batch. The thesis concludes with strategic recommendations for the current SSR program as well as future Halo vehicle projects.

Thesis Advisors: Prof. Steven D. Eppinger, Sloan School of Management
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Chapter 1 – Introduction

1.1 Thesis Background

The research for this thesis was conducted at the General Motors Technical Center in Warren, Michigan and at the General Motors Lansing Craft Center in Lansing, Michigan. The author spent six-and-one-half months on-site examining issues related to the manufacturing strategy for low-volume vehicle production.

1.2 History of the Halo Vehicle Program

For many years, General Motors (GM) has captured the automotive consumer's imagination with innovative, stylish, cutting-edge show cars. During the annual auto show circuit, a number of concept cars are displayed to the public for the purpose of creating excitement and demonstrating the design capability of GM. However, the automaker usually does not plan to put these unique vehicles into production. Most often, the concept cars are extremely expensive, one-of-a-kind fabrications produced for GM by a custom vehicle builder. The concepts do not in any way take into account the realities of actually developing or manufacturing the vehicle.

In mid-1999, the GM design group was again at work on a unique concept that would excite audiences around the world. This concept traces its lineage to the vision of the vice president of the GM design group, who challenged his staff to explore how a heritage design theme might manifest itself in a truck, vis-à-vis cars where retro designs abound. The executive director of GM's Brand Character Center then led the effort to develop potential options as to what this heritage truck might become. Both GM design executives wanted a heritage truck that was not simply a remake of a prior design, but rather, a modern interpretation of a classic theme. They wanted the concept to have clearly modern and aggressive styling, combined with readily identifiable heritage cues harking back to the famous Chevrolet trucks of decades past. This concept of blending the old with the new became known as "funkstalgia" within the GM design group.

While sketching potential concepts, one of GM's lead designers hit on a unique design that immediately caught the attention of the entire styling group. As seen in Figure 1-1, the basic sketch captures both modern and historical design cues such as large, sculpted fenders, a split-windshield and a multi-bar horizontal grill.

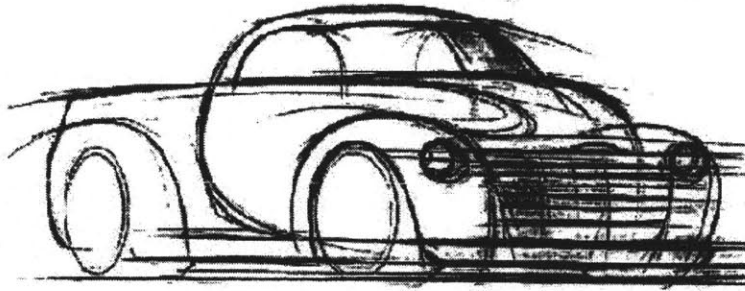


Figure 1-1. Chevrolet SSR Concept Sketch

This sketch was one of the few renderings of this concept to actually be put on paper. In August 1999, senior management reviewed the team's work and authorized the SSR be built for the 2000 auto show circuit. Designers developed the vehicle solely using math-based digital tools, in preparation for the January 2000 Detroit Show.

A few weeks after beginning work on the design, the concept was ready for virtual reality design reviews. Up to this point, the concept was called the “Slammer”, recognizing its lowered-to-the-ground, or slammed, appearance. However, the concept's name was changed to Super Sports Roadster (SSR), an appellation combining the history and heritage of the “SS” designation with the open-air attractiveness of a roadster.

After favorable management review, a full-size mock-up of the concept was milled on a CNC¹ machine directly from the digital styling data. This allowed extreme compression of the concept design process, and by September 1999, the full-size model was shown to GM's North American Strategy Board (NASB), the group responsible for authorizing further development on vehicle programs. The Board was extremely impressed and enthusiastic

¹ CNC is an acronym for “computer numerically controlled” and refers to the computerized method used to transform digital product data into a physical shape with a high degree of accuracy.

about the concept, and challenged the design team to develop a running prototype in time for the January 2000 Detroit International Auto Show.

The challenge now became how to compress what would typically be one-year's worth of design and engineering effort into just a few months. Utilizing GM's internal resources, combined with efforts from a partner design supplier, the team met the challenge of the Board and brought a running show car to the Detroit Auto Show in January 2000. The culmination of the team's effort is seen in Figure 1-2.



Figure 1-2. SSR Show Car

The response of the public and the automotive press was overwhelmingly positive. GM marketing and public relations groups received a deluge of inquiries concerning the SSR, asking when, if at all, GM would produce it. The company then surprised the automotive world in the spring of 2000, when the CEO announced that the SSR would be released as a production vehicle in late 2002.

General Motors' management deemed the SSR a worthy concept to bring to market because of its tremendous public appeal and the ability to use this one vehicle as a flagship for a GM division. The North American Strategy Board liked the idea of developing a unique model to represent each division and attract buyers to the brand. Furthermore, since the SSR concept was designed to be a viable option for production from the start, it could move rapidly into GM's future production plans. It was decided that the Halo program would commence with the SSR and then launch a unique new vehicle derived from a high-visibility show car at regular intervals. Thus the Halo program was initiated.

1.3 Halo Program Challenges

Due to the unique low-volume requirements of this specialty vehicle, a number of challenges arose for GM. With the kickoff of the Halo program, engineering and manufacturing teams worked feverishly to devise a plan to enable production of the SSR by late 2002. This plan needed to ascertain exactly how the SSR would be styled, engineered, prototyped, tested and manufactured in an accelerated timeframe.

Design and Engineering Challenges

The cycle time for a typical GM product development program currently takes approximately 36 months from the end of feasibility assessment to the start of production. In order to develop the SSR in time for a late 2002 launch, an even more aggressive schedule needed to be pursued. A financial and resource analysis was performed to evaluate the feasibility of producing the SSR via the traditional in-house GM Vehicle Development Process (VDP). The results of this analysis revealed that attempting to develop the SSR within GM could not be justified because of the high overhead costs that would need to be allocated over the low-volume program. Hence, there was no business case for maintaining the SSR in-house. At this point the SSR was turned over to the Specialty Vehicle Group (SVG) to evaluate alternate methods for producing the first Halo vehicle. After investigating various possibilities, the SVG determined that partnering with an outside design and manufacturing firm could enable the SSR to be produced while maintaining a profitable business case.

Accordingly, GM partnered with an outside supplier to do a majority of the design and engineering work on the SSR. But with GM in charge of managing the program and the supplier-partner responsible for executing it, a number of new issues surfaced. For example, *does the supplier-partner, a company that has never previously engineered a full vehicle, have sufficient technical expertise to create the SSR?* Additionally, by outsourcing the development functions of this program, *does GM lengthen the chains of communication and allow a greater possibility for design rework, thereby increasing its time-to-market?* Furthermore, *does outsourcing full vehicle product development, a core competency for most automotive original equipment manufacturers (OEMs), diminish GM's knowledge base and skills while enhancing the partner-supplier's technical expertise?* How does this affect the long-term strategy of GM if flagship vehicles must be engineered outside the mainstream of the company? These questions and others are being addressed as the Halo program progresses. This thesis does not focus on these product development issues, but instead addresses some of them at a fundamental level.

Manufacturing Challenges

Successfully tackling the challenges faced during the product development phase of the SSR is of extreme importance to the success of the Halo program as a whole. Equally important is effectively managing the manufacturing challenges faced by the program, since the overall business case is predicated on an optimized process for *both* development and manufacturing.

In order to profitably manufacture the low-volume Halo vehicles, GM needs to devise a manufacturing plan that permits highly differentiated products, based on varied product platforms and architectures, to all be manufactured on the same fixed production line. But a number of key questions arise. For example, *what is the manufacturing strategy for producing multiple vehicle models on the same line with a minimum of investment in new tooling and equipment?* *What are the manufacturing ramifications of designing and engineering a vehicle by a company not intimately familiar with the GM manufacturing systems?* and *What is the best way to balance and create product and process flexibility in the production system?* Although the subsequent Halo vehicles are still a few years away, developing a strategy to manufacture them now is crucial since equipment and processes are

currently being designed and installed for the SSR. This thesis focuses on defining and addressing the manufacturing challenges faced by General Motors in bringing the Halo vehicle program to fruition.

1.4 Project Approach

As noted previously, the objective of this thesis is to investigate and develop a manufacturing strategy for the Halo vehicle program. In this section, the project development and definition, the project methodology, the modeling process, and the thesis structure are discussed.

1.4.1 Project Development and Definition

In the past, General Motors has been highly successful at running projects on a grand scale, but not as successful at maintaining a business case for low-volume niche programs.² Much of this issue is due to the fact that the strategy for effectively producing large volumes of vehicles, using large factories with many machines and a large number of people, is not congruent with efficient low-volume automotive production. The Halo initiative is the first time General Motors is developing a manufacturing strategy dedicated to producing multiple low-volume vehicles in one plant. This program is unique in that it requires fundamentally new ways of looking at automotive manufacturing, and hence, of doing business.

The goal of this Leaders For Manufacturing internship and thesis is to help the General Motors SSR program management team devise a manufacturing strategy for multiple Halo vehicles, all manufactured on the same fixed line in the low-volume production facility. To help formulate this strategy, evaluation of relevant existing production systems is performed. Then, a station-by-station evaluation of the model changeover process in the factory is conducted. Finally, a mathematical optimization model of the manufacturing process is developed. This model will determine the optimal batch size and changeover frequency based on a number of constraining factors including changeover time between vehicles, order-to-delivery requirements, production learning curve after a changeover, acceptable inventory

² Niche automotive programs design and manufacture vehicles in small quantities with the intention of catering to a highly specific segment of the market. GM's electric car, the EV-1, is an example of a niche automotive product.

levels, and other key constraints. The output of the model will assist the GM program management, production planning and manufacturing teams in determining the frequency and optimal lot size for producing each vehicle in order to best meet the Halo business case. Additionally, this thesis will provide strategic recommendations to future Halo vehicle teams to enable each new Halo vehicle to readily integrate with the developed batch build strategy.

1.5 Thesis Structure

This thesis is organized in a similar manner to the project timeline the investigator experienced on his internship. Chapter one provides background information and a description of the problem. Chapter two analyzes the low-volume manufacturing problem from a Halo program perspective and determines the appropriate production system to use. The chapter then discusses key challenges, formulates solutions and provides recommendations for the chosen type of manufacturing system. Chapter three develops the optimization model, establishes test scenarios and analyzes the model's output. Chapter four discusses a number of the organizational and cultural issues surrounding the proposed manufacturing strategy. Chapter five presents the conclusions, which includes a review of some of the more important findings of the thesis investigation. Lastly, recommendations are made for areas where further research and additional extensions to the model would be beneficial.

1.5.1 Methodology

Rather than being fully planned from the outset, the project methodology illustrated in Figure 1-3 helped develop the thesis topic over time. The fundamental question addressed in this thesis, *what is the optimal manufacturing strategy for the Halo vehicles?* led to additional questions such as, *what does "optimal" actually mean for Halo manufacturing, what parameters need to be optimized in the manufacturing system, and what are the required goals and constraints of the manufacturing system?* The iterative steps shown in Figure 1-3 were critical in developing a final thesis project topic.

A number of informational interviews were conducted with a wide variety of subject-matter experts to gather insights about GM's current manufacturing operations and the unique aspects of the SSR and the Halo manufacturing requirements. The respondents' backgrounds covered a broad spectrum of GM's overall operations, including product development, manufacturing engineering, validation, design staff, production planning, purchasing, and quality control. Regardless of their particular backgrounds, most respondents were highly receptive to thinking about new ways of manufacturing and readily offered their thoughts on the unique manufacturing process required for the SSR and future Halo vehicles.

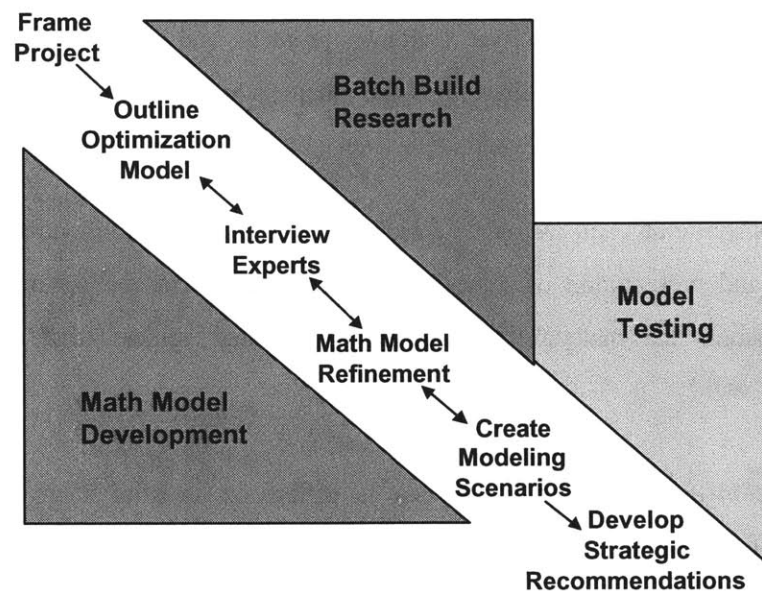


Figure 1-3. Project Methodology

The interviews varied greatly in length due to the individual respondent's background, level of involvement, and familiarity with the Halo program. In general most of the interviews lasted from one to one-and-a-half hours. Most of the interviews were conducted one-on-one or in small groups of team members from a related functional discipline. *Appendix A – Interviewing Process Guide*, provides examples of questions that were asked in the interviews. In devising the interview structure, Metzler (1996) was consulted for guidance on the interview process.

A number of major factors that influence the overall Halo vehicle manufacturing strategy emerged from the interview process. Many of these issues did not have clearly defined answers at the time, but instead were posed as questions for further investigation, as follows:

- *Factory layout and design.* How can the factory best be laid out to accommodate the existing process flow, thereby minimizing the cost of re-tooling the plant, while permitting flexibility for new vehicles?
- *Equipment and tooling flexibility and changeover.* How can tooling that is low-cost, highly flexible and accommodating of yet unknown products and vehicle architectures be designed? How can the time required for the manufacturing system to changeover between vehicle models be minimized, while doing so at a reasonable cost?
- *Material availability and changeover.* How can the production, containerization, shipment, storage and presentation of subassemblies and components be optimized? How will the factory handle the material requirements for repaired vehicles that missed their original production batch?
- *Workforce allocation and flexibility.* How can the differences in labor hours required per vehicle between different types of automotive models be accounted for?
- *Batch size and batch cycle frequency determination.* What is the ideal range of batch sizes within which to build each Halo vehicle in order to satisfy customer demands, minimize production costs, and maximize profit of the Halo program? How frequently should a cycle of vehicle models be run in order to meet the Halo program requirements?
- *Industry best practices.* What are the industry-wide best practices for automotive batch build manufacturing? How do other industries develop and maintain a successful business case for batch build manufacturing?
- *Optimization of the entire manufacturing system.* Instead of optimizing subsystems of the manufacturing system (e.g. cost or quality or delivery), how can the overall system be run in the most optimal manner? How should “optimal” really be defined?

As a result of the information acquired through the interviews, a mix of both tactical and strategic deliverables were decided upon to address the manufacturing strategy question. The tactical aspects focused on developing a changeover strategy for equipment, material and labor in the production plant. The strategic section concentrated on developing a mathematical model to optimize batch build production lot sizes. Metcalf (2001) describes a methodology for mathematical model development and testing. This methodology is modified for the Halo vehicle thesis project as depicted in Figure 1-3. Efforts at interviewing and refining the project were iterative, as indicated by the double arrow in the figure. Correspondingly, efforts intensified in understanding and assessing the components and systems (product design, equipment, material, labor and scheduling) to be considered as part of this work. After commencing the interviews and gathering sufficient background details, the creation of the math model and associated scenarios to evaluate began. Scenario creation again was an iterative step with refining the model, as more was learned about the model by testing the various scenarios.

During the batch build the research phase, a thorough understanding was gained of existing knowledge that would help solve the tactical problem. The following questions were investigated. *How do other manufacturers build niche vehicles? What is GM's high volume manufacturing process? How is the high volume car assembly process defined? and What is different about niche product manufacturing?* The goal of this research was to fully understand the issues and to uncover any existing tools at GM, other auto companies and other industries that could be useful in solving the problem.

1.5.2 Mathematical Modeling

The value of mathematical modeling in this thesis is three-fold: 1) it provides a method for understanding the sensitivity of the Halo manufacturing system to various input parameters, 2) it generates batch size results to be fed into discrete event simulations for further analysis and 3) it determines the minimum production cost for specific manufacturing scenarios. The model is particularly useful because the constraining equations and input variables in the mathematical relationships are adjustable, thus providing the user with the ability to assess

various production scenarios. See *Appendix B – Introduction to Linear Programming Optimization Methods* for an overview of basic linear programming models.

1.6 Summary

This chapter considered the history and initiation of GM's Halo program. An introduction to both the product development and manufacturing challenges faced by the Halo program was provided. This set the stage for the developing and defining the thesis project. The approach and methodology employed to develop a batch build manufacturing strategy for the Halo vehicles was then outlined. Lastly, an introduction to the mathematical modeling used to evaluate various production parameters was described.

The following chapter presents a detailed analysis of the Halo vehicle batch build manufacturing challenges and formulates potential solutions to address those issues. The chapter focuses on the concerns surrounding equipment and tooling, material, and labor as they relate to developing a flexible, low-cost manufacturing system.

Chapter 2 – Analysis of the Problem

2.1 Evaluation of Prospective Halo Vehicle Manufacturing Systems

Due to the cost constraints placed on the low-volume Halo program, the basic requirements of the manufacturing strategy are clear: devise a highly flexible, low cost production system capable of handling multiple product platforms and architectures³ on a single fixed line. Further requirements that must be addressed by the manufacturing strategy include:

- Providing the manufacturing capability to quickly move a Halo concept from auto show to production.
- Manufacturing multiple highly differentiated Halo vehicles from varied architectures, with innovative design and engineering features on the same production line at steady state.
- Designing into the system the capability to produce yet undefined products and architectures.
- Manufacturing each model in low-volume (approximately 10,000 per year) with the flexibility to balance individual product volumes as required.⁴
- Utilizing existing facilities and tooling to minimize capital expenditure.
- Relying on a high subassembly content so as to minimize the use of production floor space and enable rapid completion of the vehicle on the main assembly line.

In order to meet these requirements, three different types of production systems were evaluated: *job shop*, *mixed production* and *batch build*. Each of these systems are now discussed and analyzed in detail in connection with the Halo program manufacturing requirements. Key aspects considered when evaluating the production systems for Halo automotive manufacturing are: 1) the number of *vehicle types* to be produced, 2) the production *volume* for each vehicle type, 3) the *layout* or arrangement of equipment and processes used to manufacture the vehicles and 4) the *flow* of material through the equipment and processes.

³ The difference between *platform* and *architecture* is described in Section 2.3.1 of this thesis.

⁴ This flexibility provides GM with the ability to tradeoff volumes between products, e.g. produce 15,000 SSRs and 5,000 Halo2 vehicles or vice versa.

2.1.1 Job Shop

A job shop production system produces many different products in volumes ranging from one to a few of each product. Because typically many different products are produced in very low volumes, the equipment and tooling are general purpose. A job shop does not utilize a high level of automation, but instead relies heavily on skilled manual labor to manufacture its products. Work in process (WIP) in this type of system is high and delivery times can be long.

Few automotive manufacturers utilize job shop manufacturing to produce their vehicles because of the high cost and slow pace of production. Since this method of production is best suited to very low volume manufacturing, an example of automotive manufacturers that do employ such a production system are the makers of specialized showcars and automotive prototypes.

Low-volume auto builders such as these do not make use of an automated conveyor system or moving assembly line; instead each car is loaded onto a dolly⁵ and pushed by hand from one workstation to the next. A small team of skilled workers then spends multiple hours at their station performing the required assembly tasks. Unlike assembly performed on a high-volume assembly line, a moving conveyor does not drive the pace of production in a job shop. This type of job shop production requires a high labor content and a good deal of “finessing” to fit and adjust parts into position. This tweaking is necessary because the parts used in a job shop are not held to a tight tolerance due to the use of low-volume production tooling. For example, on a high-volume program a sheet metal bracket would be manufactured on an automated stamping press, while on a low-volume program that same part would be manually formed on a brake press. The low-volume, manual process causes greater variation in the output of the parts and therefore the vehicle is essentially handcrafted during the manufacturing and assembly process. Since each portion of the assembly can be verified and then rechecked, this manufacturing system can approach the quality output of a mass assembly procedure. However this quality parity is achieved at the expense of efficiency, cost and productivity.

⁵ A dolly is a platform on wheels or casters for moving heavy objects, like an automotive frame.

2.1.2 Mixed Production

A mixed production automotive manufacturing environment is one where multiple models are simultaneously run on a fixed production line. In this system, there is no need for planned production downtime to change over equipment or tooling between models. This capability is made possible because the equipment, material handling systems, and computer controls are highly flexible, permitting the production of many different products on the same line. In the automotive application of this system, one vehicle model can be mixed in between two vehicles of different models or styles. A high level of automation and expensive flexible tooling are the primary enablers of mixed model automotive production. The automation is required to identify each model as it reaches the station, ensure that the proper components are available at that station, and then perform the appropriate manufacturing process on that specific vehicle. The flexible tooling ensures that vehicles of different models can be produced back-to-back with no changeover of the production line between model runs.

For example, in a mixed-production manufacturing environment, automation could be used to identify the model of vehicle that is approaching the windshield glass installation station. The automated system would then initiate the correct equipment program for that specific vehicle, apply a bead of sealant in the proper locations, then use a robotic arm to select the appropriate windshield glass from a material rack, and finally place the windshield in the specified location using the appropriate pressure and duration.

Another key enabler to mixed-model production is the use of a common vehicle platform for all vehicles running down the line, discussed in Section 2.3.1. Reuse of the basic vehicle frame hardware and its associated underbody tooling is usually the focus of the mixed production approach.

Very few automotive manufacturers employ a multi-model mixed production system on their high volume vehicle lines. One that does is Ford Motor Company's Wixom assembly plant, which produces the body-on-frame Crown Victoria and the body-frame-integral Lincoln LS sedan, utilizing a high level of automation to enable simultaneous production of both cars. These different vehicle types are discussed in detail in Section 2.2.1.

2.1.3 Batch Build

A batch build manufacturing system produces fewer product models in higher volumes than the job shop production system. In the automotive case, batch building involves the scheduling and production of different vehicle models and architectures in planned quantities based on demand, cost of changeover, and plant capacity. Stated simply, batch building allows for the flexible use of a production facility to build multiple platforms on a single line. This is achieved by developing a production line that allows changeover of equipment, material and labor between batches of each product.

Honda uses a batch build manufacturing philosophy that accommodates a variety of vehicles within a specified range of manufacturing systems, denoted as small, medium or large. Honda emphasizes a “process driven product design” as a key enabler for its batch build manufacturing strategy. All products entering a batch build factory must comply with a rigid set of architectural constraints, common locating holes for underbody tooling transfer, part shingling, sequence of assembly, and station balanced work content.⁶ This high level of product discipline allows Honda to make a serious commitment to a manufacturing system that can aggressively batch build any product within that set of conditions (Scholl, 2001).

The batch system must establish a minimum batch quantity and maximum number of changeovers per unit time period based on the business plan and plant capacity constraints. These primary aspects of batch building fall under the larger category of *production planning*, which entails determining what to build, when to build it, and in what quantities to build it (Miltenburg 1995). Production planning for batch building involves economies of scale with some type of production function expression. This occurs because there is a required set-up cost to initiate the production of a specific product. For example, initiating the production of an item might require a change in tools, dies, or materials. The setup could also require a change in the production control settings, like line speed or conveyor height, as well as an initial verification run to assure that the vehicle meets output quality specifications.

⁶ The shingling of components involves an assembly sequence where the order of parts installation is important due to component overlap. For example, during body assembly an outer body panel must shingle over components that make up the inner body structure. Because of shingling, the assembly order of these parts cannot be interchanged.

2.1.4 Comparison of Options and Determination of Halo Manufacturing System

Evaluating the three production systems discussed, it is evident that with respect to the goals of the Halo program each system has its benefits and detriments. The product-process matrix in Figure 2-1 (adapted from Miltenburg, 1995) compares the three systems from the standpoint of layout and material flow, products and volumes, and manufacturing outputs. For illustrative purposes, the figure compares each of the three proposed systems against the baseline system of a *minimal variety product line* used in typical automotive plants. The figure compares the manufacturing output parameters of cost, delivery, quality, productivity, flexibility and innovativeness for all four systems. Here, it is important to differentiate between the definitions of flexibility and innovativeness: flexibility refers to the ability of a manufacturer to increase or decrease production of *existing products*, while innovativeness refers to the ability to produce *new products*.

Job shop manufacturing is not feasible on the Halo Program due to the high cost and low production output of such a system. As seen in Figure 2-1, a job shop production system is lacking in a number of key areas. Operating a job shop factory to meet the annual requirement of approximately 10,000 of each Halo vehicle would incur excessive labor costs. Such a production system would not take advantage of the work standardization and variation reduction benefits of mass production, resulting in a negative impact on quality. Furthermore, a job shop's productivity and delivery outputs are not sufficient for Halo program goals. For these reasons, developing a job shop production system was ruled out for the Halo program.

In a traditional high-volume mixed-model automotive program, significant expense is incurred in implementing highly flexible automation with the capability to easily accommodate multiple vehicle platforms in the manufacturing process. Figure 2-1 shows the weaknesses of the mixed-model production system for the Halo program. Since automation capital costs must be amortized over a relatively small number of vehicles, it raises overall production costs. Additionally, the mixed-production system is inadequate for coping with the injection of brand new, possibly yet undefined, products into the system. Therefore, implementing a mixed production system was determined not to be a feasible manufacturing strategy.

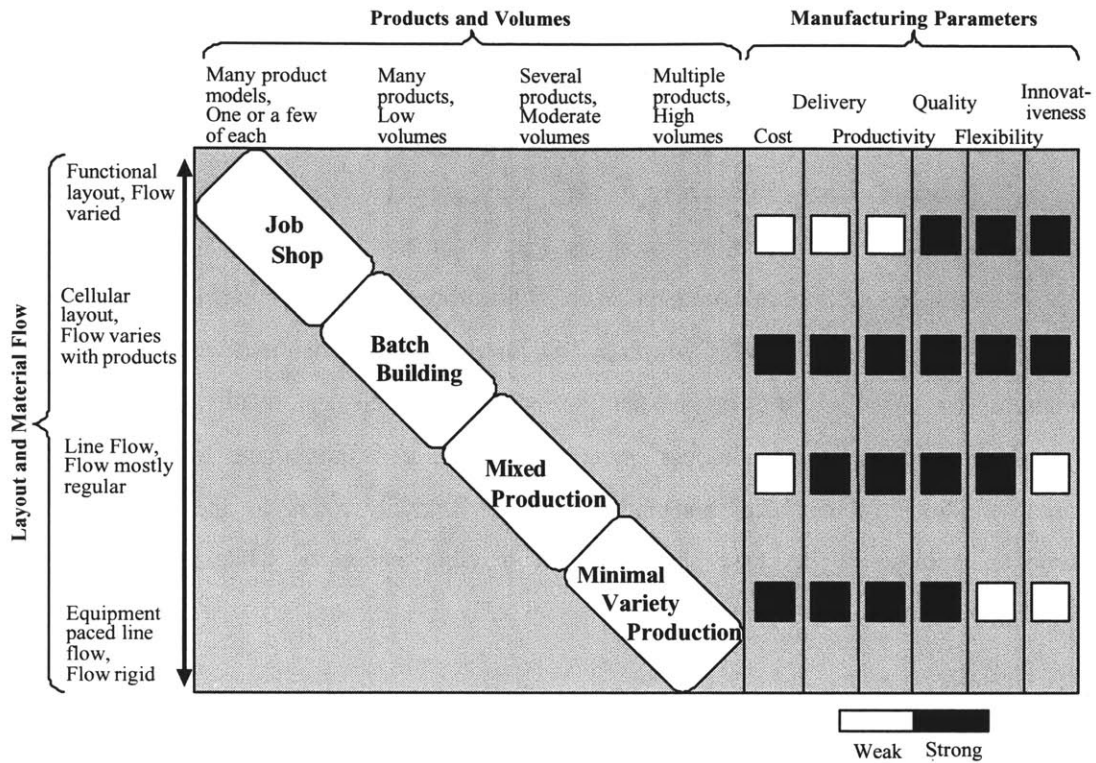


Figure 2-1. Product-Process Comparison Matrix for Halo Manufacturing Options

Observing the performance of the batch building system in Figure 2-1, it is evident that for the purpose of the Halo program, the batch build system provides the required flexibility and innovativeness, keeps capital investment to a minimum, provides sufficient capacity to meet delivery requirements, and can maintain high quality and productivity levels. For these reasons, the GM manufacturing, operations and program management teams chose a batch build manufacturing system as the production method for the Halo program.

Although the Halo program implemented a batch build manufacturing strategy, batch building is not being used at any other GM production facilities and therefore, internal benchmarking was not possible. Further investigation revealed that batch build manufacturing across vehicle architectures is very rare in the automotive industry and that GM's Halo strategy is essentially the first of its kind. A number of other industries do use batch build manufacturing effectively. In the consumer electronics industry for example, the manufacturers of products such as cellular phones and PDAs run many products down a single fixed line, with an equipment, material and labor changeover between models. This is accomplished by using

flexible tooling and equipment that can be rapidly converted from one product to another, and by careful supply chain planning to ensure that the required material is on the line at the appropriate instant. Manpower may also be reallocated from one station to another during the batch changeover if labor content varies between product models. Although these industries do utilize a batch build manufacturing strategy effectively, they are not faced with the same level of regulations and controls that constrain GM. For example, the stringent requirements of the Federal Motor Vehicle Safety Standards (FMVSS) impose constraints on the Halo production system that are not present in other industries that utilize batch building.⁷ These, and other concerns regarding the batch build Halo automotive production system are addressed in the subsequent sections of this thesis.

2.2 Batch Build Challenges and Solutions for Halo Vehicles

Although batch build manufacturing was determined to be the most feasible option for Halo vehicle production, a number of challenges need to be addressed before such a production system can be successfully implemented. The Halo vehicles will be manufactured in the Lansing Craft Center (LCC), an existing low-volume plant that currently produces the Cadillac Eldorado. The basic layout of the LCC is diagrammed in Figure 2-2.

Kirsh (1994) summarizes the general layout and function of a typical high volume automotive plant. He describes the volume plant as consisting of the three main sections: the body shop (also referred to as body-in-white), the paint shop, and the general assembly area, which contains three secondary assembly processes (trim, chassis and final). The vehicle originates in the body shop where subassemblies and individual pieces of stamped sheet metal are welded and bonded together to fabricate the vehicle body. Next, the body moves into the paint shop where it is cleaned, electrostatically coated, primed, painted with a base coat and a top coat, and then baked in a paint-curing oven. The painted body then moves through the general assembly line where component-by-component, the entire vehicle is built into a final product. The LCC follows this general arrangement and functionality of the high volume plant, but with significantly less reliance on automated systems.

⁷ The Federal Motor Vehicle Safety Standards (FMVSS) are government imposed automotive regulations that stipulate the minimum performance requirements for automotive crashworthiness. It is the manufacturer's responsibility to design, develop and manufacture vehicles that conform to these standards.

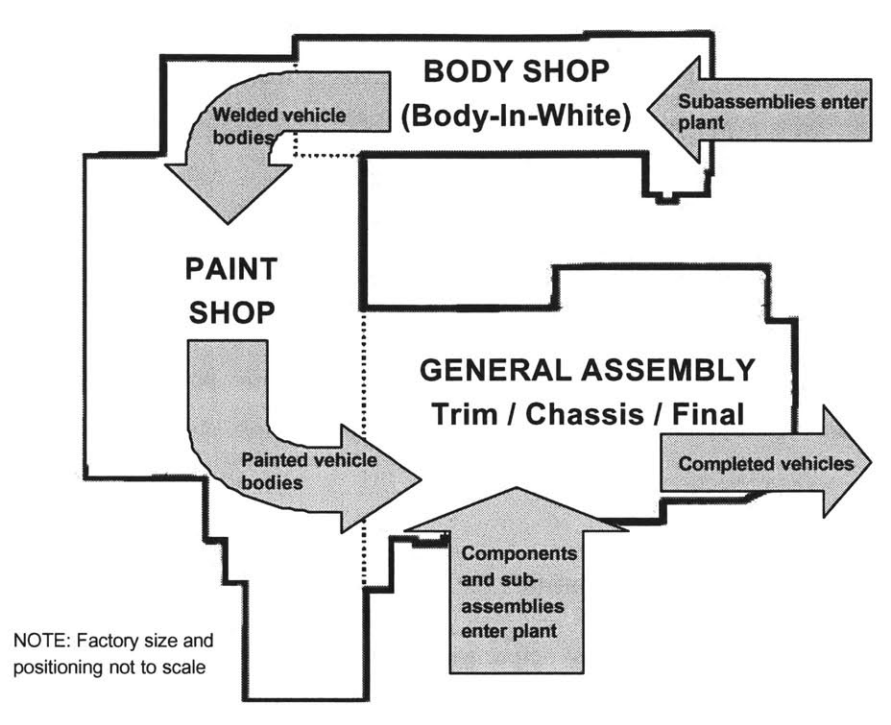


Figure 2-2. Lansing Craft Center Sub-Factory Layout

To convert the LCC from a single-product factory to a multi-model batch production plant requires careful consideration of a number of important factors. These factors affecting the feasibility of batch building at the LCC are discussed in the next section.

2.2.1 *Body-on-Frame vs. Body-Frame-Integral Processing Differences*

Attempting to produce different vehicle architectures on the same fixed line produces serious hurdles for the Halo manufacturing systems because of the inherent variation between products. Minisha (1999), in describing a hierarchy of automotive product variety, asserts that in the auto industry, the highest level at which product variety influences the production system is the *platform*. A platform refers to the engineering guts of the vehicle, such as the chassis, and is not readily apparent to consumers. With different exterior skins put on, the platform results in multiple *models*. At GM, the Chevrolet Trailblazer and the GMC Envoy are both SUV models derived from the same 4-wheel drive truck platform. Models sharing the same platform generally have the same wheelbase, but it is possible and increasingly

common to derive a stretch model with a longer wheelbase.⁸ GM's stretch wheelbase Trailblazer XL, which is derived from an extended-wheelbase truck platform, is an example of this. Finally, automakers often attach multiple *nameplates* to one model with its sheet metal skin basic intact and minor cladding and fascia changes. The Chevrolet Cavalier and Pontiac Sunfire are GM models that fit this category.

This author contends that for the Halo Program, the most important level of product variety to the manufacturing system is vehicle *architecture*, and differentiates between *architecture* and *platform*. The author defines architecture as the type of chassis design around which the vehicle is created, either a *body-on-frame* or a *body-frame-integral* design. GM produces a number of different vehicle platforms on different architectures, including a rear-wheel drive, body-frame-integral structure, and a 4-wheel drive body-on-frame structure. From a Halo vehicle manufacturing processing perspective, the most glaring difference between two vehicles lies in their architectures. This is because costly, highly specific tooling and equipment is required to locate and transport the different architectures throughout the factory, primarily in the body shop, where components must be held rigidly and precisely in place while they are welded into a structure. A comparison of the two architectures follows.

Body-On-Frame Architecture

The body-on-frame (BOF) vehicle design has been in existence since nearly the birth of the automobile. This type of vehicle architecture utilizes a steel frame or chassis that is fabricated separately from the body of the vehicle. Using today's modern manufacturing processes, the steel frame is fabricated by a combination of hydroforming, welding and mechanical fastening, and is usually produced by a tier-one supplier.⁹ The unadorned frame is shipped from the supplier to the GM assembly factory where it is built up into a complete frame assembly including engine and transmission, steering and suspension components, wheels and tires, and other running gear. The completed frame is then transported within the factory to

⁸ Wheelbase is defined as the distance in inches (or millimeters) between the front and rear axles of an automotive vehicle.

⁹ Hydroforming is a process of shaping steel tubes through the application of water at extremely high pressure. It replaces traditional stamping processes, preserving more of the steel's strength and stiffness as it goes through the forming process. It is performed at low temperatures to retain optimal material properties, resulting in high strength and stiffness, relatively low weight, precise quality and reduced material usage.

the main assembly line where it is then mated to the body. An example of the BOF architecture is presented in Figure 2-3.

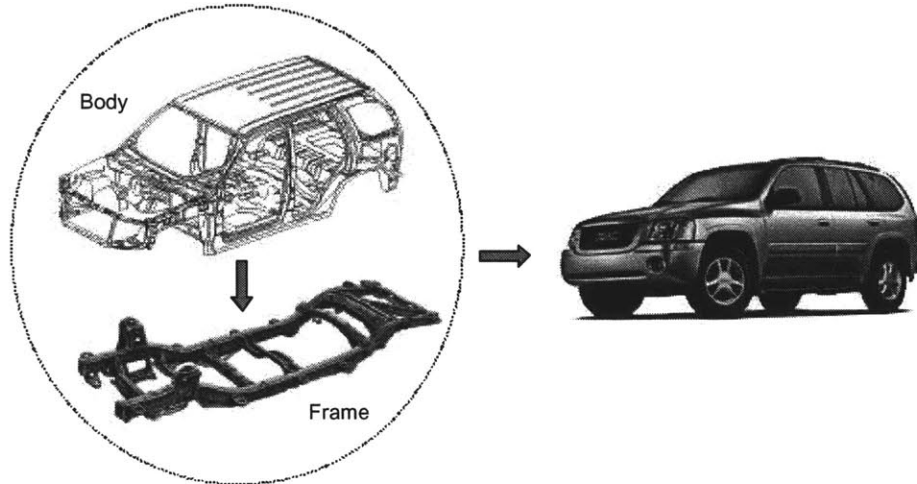


Figure 2-3. Body-On-Frame Architecture

Body-Frame-Integral Architecture

An alternative vehicle architecture is the body-frame-integral (BFI) structure, also referred to as a unibody (unitized-body) or spaceframe construction. With this architecture, the vehicle's structural rigidity is derived from the overall spaceframe – a combination of primarily steel and select aluminum components welded and bonded together. In this case, the drivetrain, suspension and other running gear are attached directly to the unibody, there being no separate frame. Since the structure of the vehicle is provided only by the strength of the welded components, accurately locating the unibody components with respect to each other during processing through the body shop is crucial. A completely welded unibody chassis before and after final assembly is shown in Figure 2-4.

The processing differences between the BOF and BFI architectures lead to the potential that some manufacturing processes in the LCC cannot be performed in the same order. For example, since the SSR is a body-on-frame design, its fuel tank is loaded and secured to the frame on the frame subassembly line. Alternatively, the second Halo vehicle at the LCC may likely be a unibody design, where the fuel tank is loaded from beneath the chassis while the

vehicle is suspended on the main assembly line. The deviation from a common manufacturing process leads to additional complexity in the factory. This is due in part to the duplicate tooling necessary to perform the same assembly task, and because operators working at a fixed position on the line now have different tasks to perform depending on the model running down the line. Furthermore, due to constraints of shingling components described in Section 2.1.3, it is not possible to simply move the installation of certain components to another location on the line. Since the Halo program desires to produce vehicles from different architectures on the same production line at the Lansing Craft Center, successfully addressing this processing variation is of primary concern.

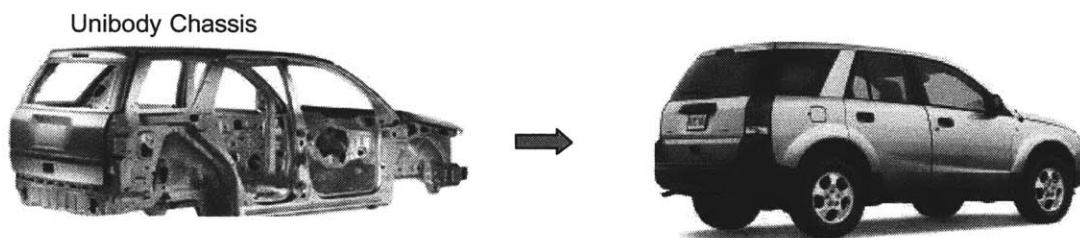


Figure 2-4. Unibody Architecture

Product Development Recommendations for Handling Multiple Vehicle Architectures

Although running multiple product architectures and platforms on the same line poses a serious challenge for the Halo program, a number of product development options are available to handle this production requirement, as follows.

- *Design products to the Halo “box” requirement* – Any Halo vehicle design should fit within the maximum cubic space or volume defined by the factory’s constraints. If manufacturing engineering can develop tools and equipment to accommodate any type of vehicle within this box, it will enable the Halo product development teams to have a range of flexibility for their product designs within this overall size envelope. Designing a vehicle outside of this acceptable volume means the vehicle may not be able to be produced at the LCC. For example, in the paint shop, phosphate dip tanks are capable of fully submerging a vehicle of a certain maximum size. Designing a vehicle any larger than these established dimensions would render it unproduceable in the LCC.

- *Product designs should have no body shop options* – Since expensive, and often times unique, weld guns and locating hardware are required to handle product options in the body shop, eliminating body shop options minimizes unique tooling proliferation.¹⁰
- *Utilize common product hardware across model designs* – Attempting to minimize variations between models by commonizing components will help reduce the number of unique tools needed in the factory. This complexity reduction is particularly critical in the general assembly factory, where differences in vehicle architecture (car vs. truck) force the need for multiple, unique single-spindle tools to drive and secure all fasteners.¹¹ Areas that should be considered for commonality include: 1) subassembly module and piece part component reuse across platforms or architectures, 2) shared fasteners and torques where possible, and 3) common location points for installation of components and subassemblies.

2.2.2 Tooling and Equipment Changeover

Changeover Tactics

It was initially thought that for the tooling and equipment changeover strategy, it might be possible to convert over the hardware in all three sub-factories at the same instant in time. This would have enabled all processes within the LCC to switch over and process the same vehicle model simultaneously. However, it quickly became evident that this strategy would not be feasible. Since the automotive production line used in the LCC is a moving conveyor system inherited from the existing plant, a simultaneous changeover presents two options: 1) stop the entire conveyor at one time, purge all the existing work on the conveyor, and replace it with another model and 2) wait until the last unit of a specific model has worked its way through the entire manufacturing process, next changeover all the equipment, and then begin production of a new model. Both options are infeasible because there is insufficient factory floor space at the LCC to pull vehicles off the line and store them, and waiting until the last

¹⁰ Body shop options use different metal components and weld equipment to fabricate products with a unique dimensions or features. Examples of body shop options are a trunk versus a hatchback model.

¹¹ Single spindle tools are hand-held pneumatic or electrical nut-runners (also referred to as nut-drivers) used by production operators to drive mechanical fasteners (e.g. nuts and bolts) to a specified torque.

vehicle is completely processed would accrue an inordinate amount of idle time from stations upstream that are waiting to changeover.

Recognizing that a concurrent changeover plan was not viable, the revised mainstream direction established for the Halo program was to changeover all of the equipment and tooling in the factory in a rolling “changeover bubble”. This means that when the last vehicle in a batch of one model leaves a station, the next arriving skid is empty and the operator utilizes the non-production time to switch over the equipment at his or her station. The initial target established by the batch build strategy team for the duration of this changeover bubble was 30 minutes. This baseline target is the maximum amount of time permissible to maintain the factory’s required production capacity for the planned demand. A changeover bubble greater than 30 minutes will not allow the factory to meet annual demand requirements.

The main changeover bottleneck driving the estimated 30-minute time are the framer gates in the body shop – large pieces of complex welding equipment that must be manually changed and set-up for each model. Although this is an issue, the framer bottleneck can be buffered or the body shop line can be run at over speed to compensate for the 30-minute downtime. However, from the standpoint of the overall manufacturing strategy, the area of the production process that matters most is the final area of the general assembly factory. In this area, completed vehicles are shipped out of the plant. Therefore, any downtime in the final area affects actual factory output and hence, revenue generated by the plant.

With an expected line cycle time of approximately six minutes per station, a 30-minute rolling bubble means that five empty skids will pass through the station during the changeover window.¹² This equates to a loss of five vehicles per station for each model changeover when the bubble passes through the factory, as seen in Figure 2-5.

¹² This six minute cycle time was derived from the requirement to be able to produce 16,480 Halo units annually on one shift. The number of jobs per hours is: $\frac{16,480 \text{ jobs}}{\text{year}} \times \frac{1 \text{ year}}{235 \text{ production days}} \times \frac{1 \text{ day}}{7.23 \text{ work hours}} = \frac{9.7 \text{ jobs}}{\text{hour}}$

which translates to a cycle time of: $\frac{60 \text{ minutes}}{\text{hour}} \times \frac{1 \text{ hour}}{9.7 \text{ jobs}} = \frac{6.2 \text{ minutes}}{\text{job}}$

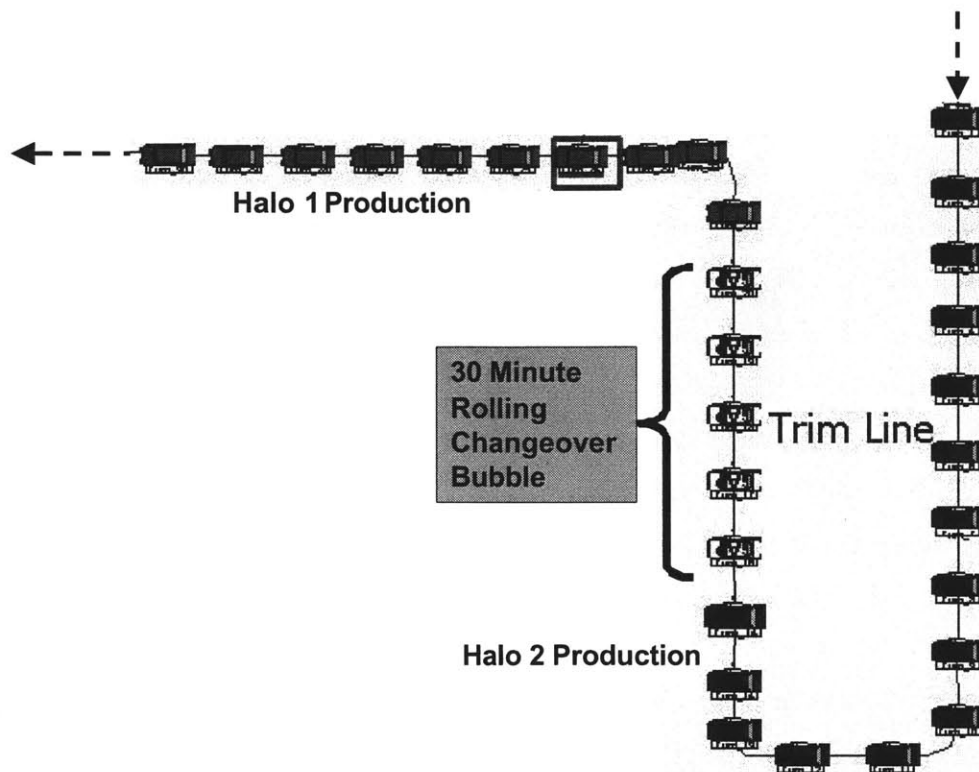


Figure 2-5. Rolling Changeover Bubble

The batch build manufacturing system will be highly sensitive to overall changeover time of the system. A major driving factor to the system changeover time is the tooling changeover time, e.g., the time required to switch all the equipment and processes from one vehicle and set them up to run an alternate model. Obviously, the longer this equipment changeover time, the greater the cost of factory downtime and hence, the less efficient the overall system as measured by hours per vehicle, plant capacity and return on investment.

A primary aspect of this thesis project involves analyzing the changeover process for the entire production system at the LCC in order to evaluate methods for reducing the changeover time required between model runs. As part of a batch build strategy team, the author was charged with performing a tooling and equipment monument changeover analysis at each station in the vehicle production process flow.¹³ These activities included the following:

¹³ A “tooling monument” refers to a large, fixed piece of tooling that is not easily transported from one location to another within the factory.

- Studying the body, paint and general assembly sub-factories in the LCC to develop a detailed understanding of the current process flow, equipment requirements and line layout.
- Participating in body, paint and general assembly “wall walk” review sessions conducted by the manufacturing engineers responsible for each assembly process. The goal of these meetings is to review the components, assembly process, and equipment required at each station in general assembly.
- Reviewing the planned SSR and Halo2 production process flows and assembly sequences with the engineering leads and manufacturing engineers for each product. Documenting the current mainstream direction for the changeover process for tooling monuments at each station in the factory. Information gathered on the changeover process included:
 - Identifying all tooling and equipment monuments and their location in the LCC process flow.
 - Comparing the assembly sequence for each vehicle at each station and identifying common processes.
 - Evaluating components and subassemblies installed at each station to understand tooling and equipment required to install those components.
 - Assisting with the development of the changeover process at each station that minimizes the changeover time per station.
 - Identifying the bottleneck processes in each factory and developing a plan to manage or eliminate them.
- Assisting with the development of a strategy for single-spindle tool utilization and changeover. Evaluating methods to minimize the proliferation of single-spindle tools as a result of significant processing differences between BOF and BFI architectures. These processing differences arise because cars (BFI) and trucks (BOF) require different fasteners with different torque specifications. Each Halo model is to a large extent,

handcuffed by the previously validated fasteners specifications passed down from the mainstream product program. Accordingly, it is difficult to specify a new fastener for an existing platform in order to drive commonality between multiple Halo vehicles. Figure 2-6 depicts the usage of numerous single-spindle tools hanging from overhead carriers on the chassis assembly line.

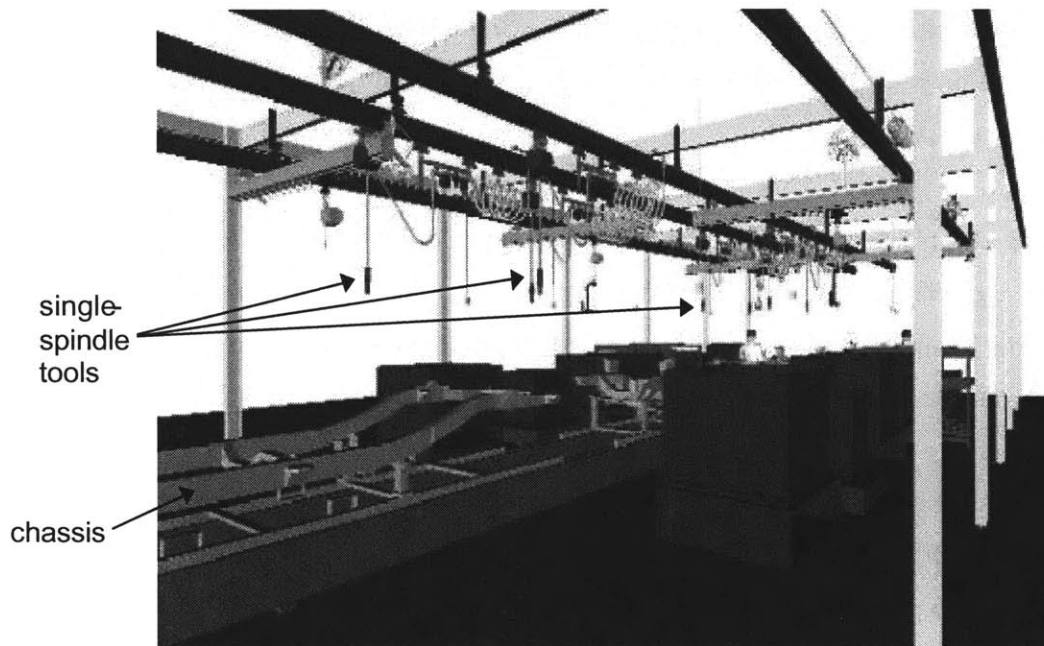


Figure 2-6. Single Spindle Tool Configuration on the Chassis Assembly Line

An example of the equipment and tooling evaluation for the body, paint and general assembly sub-factories are displayed in Figure 2-7. To illustrate the analysis for an entire sub-factory, a complete list of the tooling changeover plan for each station in the body shop is provided in *Appendix C – Equipment and Tooling Analysis By Station*. Investigating each station in detail provides the opportunity to perform a design-for-changeover (DFC) assessment of each process. Similar to design-for-manufacturing (DFM) or design-for-assembly (DFA) for products, the DFC evaluation allows industrial, manufacturing, and product engineers to collaboratively determine the optimal methods for minimizing the changeover time for equipment at each station and process. Much like the “single minute exchange of dies” (SMED) program initiated by the Japanese in their stamping factories to rapidly changeover

equipment while minimizing downtime, the Halo manufacturing team should use a bottleneck-focused setup time reduction analysis to implement quick changeover tooling and hence drive changeover cycle time reduction.

As a result of this station-by-station analysis, a number of insights were gained and key changeover strategies developed. Although the baseline plan calls for a 30-minute rolling changeover, the manufacturing engineering team has discussed reaching a stretch goal of performing a full changeover in fewer than one vehicle, i.e., within six minutes. After evaluating the changeover process and related changeover time for every station in the body, paint and general assembly factories, it appears that the changeover bottleneck is the welding framer gates with an estimated changeover time of 10 minutes. Although this data has not been validated in a production environment and the welding equipment is not yet available in the LCC, the manufacturing engineering team believes 10 minutes is a realistic, but aggressive, bogie. Assuming this new changeover time is achievable, the loss per changeover is reduced from five vehicles to fewer than two vehicles. The significance of this is that a 10-minute changeover enables a higher degree of flexibility in the system by allowing more frequent changeovers between vehicle models.

The reduced potential changeover time of 10 minutes is included in the mathematical model discussed later in this thesis, for evaluating the sensitivity of the system to changeover downtime. Once production hardware is set-up, time studies can be taken at each station to validate the actual changeover time of the designed equipment. After the actual baseline changeover time is established, implementing steps to reduce that time will be of primary importance if a 10-minute goal is to be reached.

LINE	STATION #	PROCESS	PARTS INSTALLED	TOOLING / EQUIPMENT	CHANGEOVER PROCESS	X-OVER TIME (approx)	NOTES
Underbody	B020	Seal, load and weld rockers, cross-sill and rear bulkhead panels. Perform additional manual underbody spot welds	SSR: LH / RH rocker subs, cross-sill assembly, RR bulkhead assembly Halo2: LH / RH rocker subs, tunnel reinforcement	Underbody base fixture, hanging weld guns (common for rockers, unique for tunnel reinforcement), sealer pump	Manually roll out/in underbody bases on casters. Swap weld guns.	10 min	UNDERBODY BASES: fixturing stored near line and manually rolled out/in on casters. If idle underbody fixturing is too close to in-use hardware, may move to a storage area. WELD GUNS: utilize separate quick-change guns heads for SSR & Halo2. Air & water will quick disconnect, power may need manual connection. Halo2 will carry the cost of implementing weld gun tool changers. SUBASSEMBLIES: No subassemblies done in LCC - floor, rear comp and motor comp arrive in LCC as complete assemblies from partner-supplier. ISSUE: Common sealer must be used across all Halo products or additional hardware/changeover is required.
LINE	STATION #	PROCESS	PARTS INSTALLED	TOOLING / EQUIPMENT	CHANGEOVER PROCESS	X-OVER TIME (approx)	NOTES
Base Coat	ELPO	Dip & Spray (multiple processes)	N/A	ELPO tanks and spray nozzles	No changeover required	5 min	Spray nozzles will be set-up to accommodate multiple products, no need to change nozzle position during changeover. Tanks are being redesigned accommodate Halo 'box' - tanks walls will be raised to fit.
STATION #	PROCESS	PARTS INSTALLED	TOOLING / EQUIPMENT	CHANGEOVER PROCESS	X-OVER TIME (approx)	NOTES	
17-007	Common: Cockpit & component install	COMMON: Cockpit, RH/LH cowl trim, LH/RH knee bolster, LH/RH bright strip, hood cable routing, hood blanket, secure up/down bolts through cross-car beam end brackets.	COMMON: BOP IP load assist tool	Use same load assist. Disengage SSR slave fixture.	10 min	Plan is to use BOP tool for all Halos. For SSR the tool's pins will connect to a cradle that holds the IP from below. Halo2's IP design should be BOP compliant and will work with the load tool as-is.	
	SSR: (common) + components	SSR: Engine wire harness, cockpit wire harness to BBEC, Secure R/L C/C attachments through hinge pillars (2 per side) to cross-car beam	SSR: Slave fixture to cradle cockpit from underneath	N/A	N/A	---	
	Halo2: (common) + tonneau	Halo2: attachments to plenum & antenna	Halo2: N/A	N/A	N/A	---	

Figure 2-7. Tooling and Equipment Changeover Analysis Sample

In order to reach the changeover time goal of 10 minutes, the following strategies are recommended for the LCC:

- *Utilize transport carriers with “flip-up” design tooling pins and locating details* – There is insufficient room in the LCC for storing multiple sets of transport skids for each architecture or platform. Utilizing a common skid design with rapidly configurable locating features eliminates the need for storing multiple skid types.
- *No build station will change function as part of changeover* – Due to the impact on operator training and safety combined with the negative impact on station downtime, it is recommended to keep all station functions constant. For example, a load-and-install station will remain a load-and-install station, and a fluid fill station will remain a fluid fill station.
- *Station changeover should require no special skills or tools* – Since only a few skilled trades operators work in the LCC, equipment changeovers must be able to be performed by the production associate who works at that station. If special job classifications or certifications are required to changeover stations in the plant, it will be impossible to meet the 10-minute changeover goal due to insufficient skilled labor resources.
- *Station changeover should require no equipment lock out* – Similar to the prior recommendation, equipment changeovers must be capable of being performed by regular production associates without locking out equipment. Only members of the skilled trades group can perform equipment lockout. However, the skilled trades group has insufficient capacity to changeover multiple stations in the LCC in 10-minutes if changeovers are required.
- *Utilize flexible tooling with self-storing tool changeover details* – Implementing flexible tooling that can be changed in-place, as opposed to dedicated roll-away tooling, will save factory floor space and reduce the time required to changeover a station.
- *Minimize the number of single-spindle tools per station* – Utilizing common shared fasteners and torques where possible will help reduce the number of unique single-spindle tools needed in the factory. Reducing the number of tools per station will help to minimize the build station complexity depicted in Figure 2-6.

2.2.3 *Material Presentation and Changeover*

Equally important to developing a robust equipment changeover strategy is implementing a well thought out material changeover plan. There is little benefit in developing equipment capable of a rapid changeover if material is not available for the next Halo model. An exceptionally lean material system is needed since there simply is insufficient space in the LCC plant to simultaneously store material for multiple vehicles. Therefore, the basic requirements for a material system are: 1) to enable rapid material changeover between models, 2) to minimize build station footprint and 3) to maximize container utilization. A number of material recommendations were devised in coordination with the batch build strategy team. Halo material strategy must incorporate:

- *Just-in-time (JIT) delivery for most components and subassemblies in order to minimize required material storage in the LCC.* However, it may be necessary to maintain an in-plant buffer for critical items, i.e. the topstack assembly, since roof panels are painted in house at the LCC, but the panels are then shipped to a supplier for assembly into the complete roof mechanism before being trucked back to the LCC. Since topstack installation into the vehicle is one of the first processes on the general assembly line, a buffer of completed topstack assemblies will need to be maintained so as to prevent the line from running dry due to part stock outs.
- *Flexible containers capable of handling the same type of part for multiple vehicle models.* This prevents the need to have four types of containers to secure and transport the same type of part. For example, it is preferable to design a single container to accommodate all instrument panels, rather than using a separate type of container to hold the instrument panel for each Halo model.
- *Highly modularized subassemblies to minimize the number of unique parts that must be containerized and stored on the line.* Subassemblies that have a high level of work content already included will require less labor, material, floorspace and equipment to assemble, than if the components in the subassemblies are assembled on the main line.

- *Targeting batch sizes to full container utilization in the body shop.* Doing so will leave empty racks at the end of each batch and will prevent unnecessary storage of partially empty racks and accompanying material until the next run of that model. This scheme enables containers and racks to be completely empty and ready for return to the supplier at the end of each batch.
- *Sequencing parts and subassemblies for the general assembly factory.* Since batch sizes in the general assembly factory will vary due to the management and processing of “stragglers”, it is advisable to have parts released to the line only when a vehicle has started through the factory.¹⁴ However, this means that for sub-assemblies and parts requiring unique racks, the last rack may be partially empty and may have to be stored in an off-line material holding area.
- *Container material in batch sizes that are divisible by 30.* Vehicle production will also be sized in batches that are multiples of 30. This permits maximum flexibility of rack sizes for larger subassemblies and components. The major commodities requiring unique racks can then be shipped in quantities of 1, 2, 3, 5, 6, 10, 15 or 30 per container or rack. Since the minimum batch size is 90 to prevent more than one changeover per shift, using multiple of 30 for the containerization strategy is logical and easy for the material handlers in the LCC to work with. A material strategy must still be established for rejecting incoming parts and for parts not used due to a reworked vehicle body that is separated from its assigned batch.
- *Kitting of parts and subassemblies if cost-justified.* Kitting has benefits similar to sequential parts delivery. It reduces the amount of parts at the individual assembly station on the line and thus allows more variety. As a consequence of the constrained line-side space in the LCC, there may not be a sufficient footprint for storing required materials. Kitting all of the details required for one assembly station into a single tote (or bin) allows for more components to be delivered to the line in a JIT fashion. In this manner, space for

¹⁴ “Stragglers” are vehicle bodies found to have cosmetic defects that must be re-run through the paint process. Reprocessing a straggler in the paint factory may cause that delayed vehicle to miss the rest of its batch when the original batch reaches the general assembly factory. This issue is discussed further in Section 2.2.4.

only one bin may be required, whereas previously room for four or five bins per station was necessary. Kitting may be performed either in-house or by a partnership with an outside material stager depending on cost justification.

- *Minimizing material handling.* Handling a component does not directly add value to it and therefore, it is an activity that should be minimized. If and where possible, suppliers should be used to package parts so they can be taken directly to the assembly line. This process is already performed in certain areas of GM's plants. For example, the body assembly plant receives stamped outer panels from suppliers in custom containers taken directly to the line and never touched by a GM material handler in the plant. They were last handled at the stamping plant and next touched by the GM operator about to install the outer panels on the vehicle. The empty racks are then returned to the supplier's stamping plant for replenishment.

These and other material considerations must be taken into consideration when devising a material plan for each Halo part and subassembly.

2.2.4 Straggler Strategy

Like any other automotive production plant, in the LCC's paint factory a certain percentage of vehicles go through a rework loop due to paint defects. In any paint shop, these defects can be caused by foreign material in the paint surface, inconsistent color across a painted surface, or a cosmetic flaw introduced during the painting process. These types of rework issues typically occur on anywhere from 2% to 15% of vehicles processed through a paint shop system. Repaint and respot rates are typically higher for modern tri-coat paint finishes used on premium cars, and planned for use on future Halo products.

A high-volume dedicated or mixed-production plant has a rework loop that sends a vehicle back through the paint process or to an offline manual respot area as necessary. Once the rework is complete, the vehicle is injected back into the process and continues on through the process flow. However, on the Halo program, batch building vehicles implies that a vehicle body may enter and leave the paint rework loop, and move to the general assembly factory

while a different model is set up for processing. When this occurs, the reworked body will have to be detained in an off-line area for reintroduction into the process when its model type is ready to run again. This delay in processing will cause WIP to build up in the factory, with the possibility of insufficient floorspace to store the reworked bodies. Resolution of this issue will require additional discrete event simulations to formulate a solution.

2.2.5 Order to Delivery Requirements

An additional key consideration for the manufacturing strategy development is the order-to-delivery (OTD) requirement. The OTD metric is a GM measure of the time that elapses between the receipt of a customer's order and delivery of the vehicle. The Halo strategy team has agreed that in order to attempt to meet OTD requirements, each vehicle should be run at least once per week. But how many units should be run per week and how often should the factory set up for each model? In a batch build manufacturing system, two important parameters of the system are *batch size* (also referred to as lot size) and *cycle frequency*. As seen in the hypothetical example in Figure 2-7, with four Halo vehicles running in the LCC, each vehicle must be produced in a specific batch quantity.

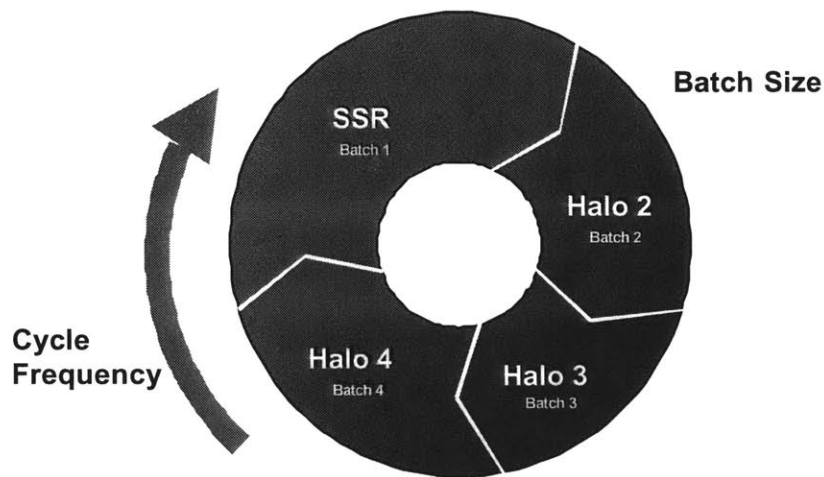


Figure 2-7. Batch Size and Cycle Frequency

The size of each batch for the four vehicles then determines the frequency at which the batch cycle repeats. For example, in a production system capable of making four products at a rate of 150 units per day, a cycle of 10 days allows for 300 units of the SSR in the first two days; 450 units of Halo2 in the next three days; 150 units of Halo3 in the following day; and finally 600 units of Halo4 in the final four days. Therefore, 10 days would elapse between the initiation of a batch of SSR vehicles.

The key questions to answer for the Halo vehicle production system are, *given the constraints of the system, what is the optimal batch size and how frequently should any one model be run?* An optimization model will help to respond to these questions.

2.3 Summary

This chapter analyzes the manufacturing challenges of the Halo vehicle production system. In doing so, it compared the *job shop*, *mixed production*, *batch build* and *minimal variety* production systems in the areas of cost, delivery, quality, productivity and flexibility. The logic behind selecting batch build as the Halo manufacturing strategy is detailed and the concept of a factory changeover is introduced.

The chapter also explains the notion of a *vehicle hierarchy*, focusing on the difference between a vehicle *platform* and *architecture*. It then describes the challenges and potential solutions to enable production of both *body-on-frame* and *unibody* vehicles on the same fixed manufacturing line.

The chapter concludes by explaining the *order-to-delivery* metric and the associated production scheduling constraints imposed by the metric on the manufacturing system. The definitions of *batch size* and *cycle frequency* for the Halo manufacturing system are explained, which leads to the questions about optimal batch size and cycle frequency. The following chapter develops a batch build mathematical optimization model and runs the model under various production scenarios to evaluate feasible batch sizing options.

Chapter 3 – Batch Build Optimization Model Development

3.1 Utilization of Math-Based Tools at General Motors

As competition in the automotive industry becomes increasingly fierce and profit margins shrink, automotive manufacturers such as General Motors look to streamlining development and production costs. An area of strong interest at GM is the use of math-based tools to reduce time and cost for operational processes throughout the corporation (Nguyen, 2001).¹⁵ These math-based tools include CAD systems for product design and validation, simulation software for factory layout visualization and evaluation, and analytical programs for production planning optimization.

The optimization model developed for this thesis project is intended to be a production-planning aid, utilized by the Halo program's operations, manufacturing and program management groups. However, since this math-based tool has a feasible scope and utility, its output must be understood within the bounds of its capabilities. Its successful implementation and utilization requires careful planning and coordination from both the technical and organizational perspectives.

This chapter examines the need for, and development of, a math-based tool to address the production-planning problem for multiple Halo vehicles. This section represents a large part of the actual research and development work done on the project.

3.2 Optimization Model Driving Factors

There are two underlying opposing forces that create the need for a linear program to solve the batch build optimization problem. On one hand, in order to minimize overall production costs, the manufacturing system should changeover between models as infrequently as possible. This minimizes the labor and indirect material costs associated with the changeover,

¹⁵ "Math-based" is a GM term that refers to the use of computerized or mathematical analysis tools, rather than the physical system, to formulate strategies and predict behaviors. By reducing the need to perform tests with the physical production system, the time and cost needed to set-up the manufacturing system can be significantly reduced.

as well as the opportunity cost of vehicles lost during the changeover downtime. Therefore, in the *unconstrained* case, the system is designed to minimize changeovers and maximize production output. In this hypothetical case, with four Halo vehicles running at full annual volume (Figure 3-1), a changeover only occurs at the end of each quarter year and batch sizes are as large as possible.

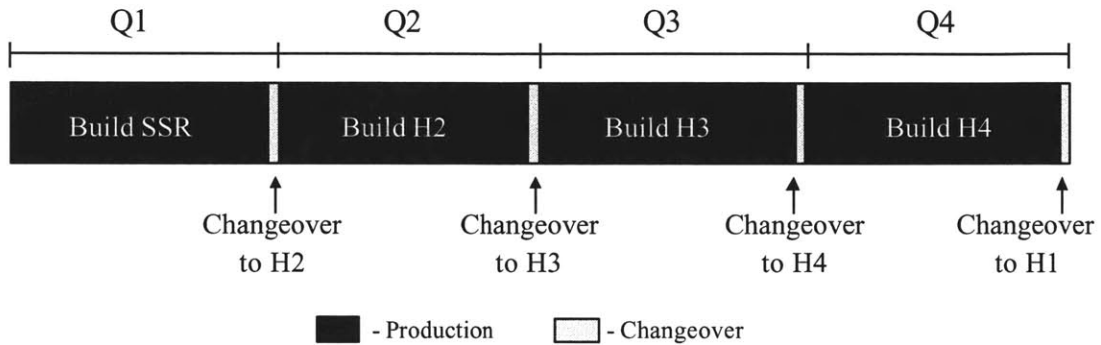


Figure 3-1. Batch Build Production and Changeover Plan - Unconstrained Case

However, this unconstrained case is unrealistic, in that it does not account for the other driving factors that reduce batch size and increase changeover frequency in the system. One of GM's corporate initiatives is to reduce the order-to-delivery time, described earlier, down to a minimum feasible level. Constraining the production system by adding in OTD restrictions such as maximum lot size and maximum time between production cycles of a vehicle model will produce a changeover output that appears as in Figure 3-2. This type of output defines how large each batch should be and how frequently to produce any one of the Halo models.

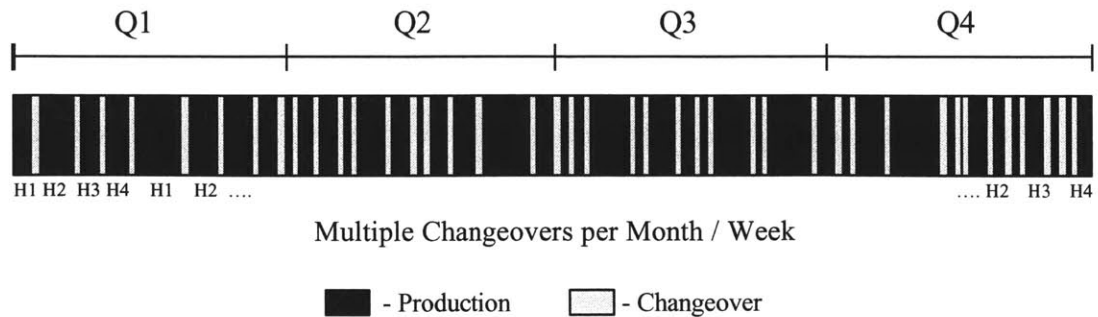


Figure 3-2. Batch Build Production and Changeover Plan - Constrained Case

3.3 Model Scope

The goal of the optimization model is to develop a decision support tool that can be used to help determine optimal batch sizing and cycle frequency for the Halo vehicles in the production facility. But first, it is important to clearly define the meaning of *optimal* for this mathematical model. By optimal, it is meant balancing the impact of a number of input parameters and production constraints in a manner that produces acceptable results for the Halo program. Optimal does not mean that the output of the model is intended to create a single ideal solution, but rather that the output can be used as a starting point in detailed production planning.

The model is a linear program devised to optimize key program parameters subject to multiple constraining factors. The primary goal of the model is to optimize an objective function that minimizes overall production costs, including changeover costs, inventory holding costs, and cost associated with production loss due to learning curve effects. Secondary driving factors of the objective function are to maximize quality and minimize plant disruption.

The model can be used as a tool to conduct scenario analysis¹⁶ when making important strategic decisions. Scenario analysis is a process that involves estimating and evaluating the best- and worst-case future scenarios, and then developing strategies that are robust within those scenarios. It involves creating strategies that will work over a wide range of possible future states. As an example, scenario analysis can be applied to the Halo program decision-making process. First, the two extreme future scenarios must be defined, such as build only one vehicle in the plant and batch build four vehicles in the plant. Based on these two extremes that *very likely bound all possible conditions*, how does GM's created strategy fare under each scenario?

A key to developing a robust model output is incorporating the appropriate set of constraints. In order to formulate the proper set of constraints, team members from the manufacturing, operations, production planning and management teams were interviewed. Based on their

¹⁶ Michael Porter, *Competitive Advantage*, p. 445

inputs, a constraint set was developed that accurately captures the limitations of the production system for the Halo vehicles. The following partial list of constraints to which the model is subject:

- Maximum plant production capacity
- Meeting forecasted market demand and order-to-delivery metrics
- Yearly/monthly/weekly production requirements
- Minimizing changeover time and cost
- Minimum batch size to reduce the impact of start-up learning curve for each model changeover
- Maximum and minimum batch sizes satisfying the containerization strategy to meet the requirements of the constrained floor space

Since the Halo vehicles will not be in production at the time the model is completed, it will not be possible to use the output of the model to run an actual factory production schedule. Instead, the output from the model will be fed into a discrete event simulation software package that will model the factory's behavior and output based on various batch build policies.

The model will only answer the question, *what is the lowest production cost, optimal batch size, and cycle frequency for a given set of inputs and constraints?* The model results will then be analyzed for validity, feasibility, and impact on the production system.

3.4 Linear Program Optimization Modeling Approach and Algorithm

Graves (1999) describes manufacturing planning and control as a “process to address decisions on the acquisition, utilization and allocation of limited resources to production activities so as to satisfy customer demand over a specified time horizon. As such, planning and control problems are inherently optimization problems, where the objective is to develop a plant that meets demand at minimum cost or that fills the demand and maximizes profit.”

Within that context, the modeling approach used was the simplex linear programming optimization method. It was selected because of its ease of use and applicability to a wide variety of operations planning problems. *Appendix B – Introduction to Linear Programming Optimization Methods*, describes the simplex linear programming method in greater detail.

3.5 Modeling Formulation

To formulate the linear program (LP), four key types of parameters must be developed: 1) *input variables*, 2) *an objective function*, 3) *decision variables*, and 4) *constraints*. The following section develops each of these parameters in detail from a mathematical standpoint. The sample of the linear program optimization model with four time periods is presented in *Appendix D – Halo Production Optimization Model*.

3.5.1 Inputs and Parameters

The user of the model can specify most of the following input variables. These variables are typical production bounds such as plant capacity per shift, changeover cost per model and, per unit inventory holding cost. The time period, T , and the total number of unique vehicles permitted in the system, I , are fixed in this model. Two other input variables require detailed explanation. One is a_{i1} , the amount of production resource required per unit of production of vehicle i . The production of all vehicles utilizes a single shared resource, namely, manufacturing capacity. Manufacturing capacity is based on the single fixed manufacturing line, its equipment and operators. Therefore, this variable states that to produce one vehicle uses up one unit of baseline production capacity. This unit can vary by vehicle, e.g., a car may take 0.9 units of production capacity to produce while a truck could take 1.1 units of capacity due to differences in labor hours required per vehicle as described earlier.

The second variable to define is a_{i2} , the amount of production resource required for set-up of production of vehicle i . This variable refers to the amount of production resource, or capacity, that is lost as a consequence of performing a changeover. The baseline assumption for this variable is that all changeovers take 30 minutes, i.e., five units of production capacity are lost per changeover. The variable can be modified as required to evaluate varied production scenarios.

The model's inputs and parameters are as follows:

- T number of time periods (the model uses 50 production weeks in one year)
- I number of unique vehicles produced (the model uses 4 unique Halo models)
- a_{i1} amount of the production resource required per unit of production of vehicle i
- a_{i2} amount of the production resource required for set-up of production of vehicle i
- b_t amount of the production resource available in time period t
- d_{it} demand for vehicle i in time period t (deterministic value based on number of allowed orders for a Halo vehicle in a time period)
- cp_{it} unit variable cost of production for vehicle i in time period t
- cq_{it} unit inventory holding cost for vehicle i in time period t
- cy_{it} set-up cost for production for vehicle i in time period t

3.5.2 Decision Variables

The decision variables usually measure the amount of resources to be allocated to some purpose or the level of some activity, such as the number of products to be manufactured in a given time period. This model uses decision variables for:

- p_{it} production quantity of vehicle i during time period t
- q_{it} inventory quantity of vehicle i available at the end of time period t
- y_{it} binary decision variable to denote a set-up (changeover) of vehicle i in time period t

3.5.3 Objective Function

Once the decision variables have been defined, the next step is to define the objective, which is typically some function that depends on the variables. For the Halo vehicle optimization model, a cost minimization, mixed-integer linear program can be defined with the objective function:

$$\text{MIN } \sum_{t=1}^T \sum_{i=1}^I cp_{it} p_{it} + cq_{it} q_{it} + cy_{it} y_{it} \quad \text{Equation 1}$$

Equation (1) can be readily decomposed into its individual components. First, the MIN expression indicates that the model is minimizing the objective function, or production cost. Next, the two summations, $\sum_{t=1}^T$ and $\sum_{i=1}^I$, denote that the model will sum the production cost over all time periods (50 weeks) and vehicle models produced (4 unique models, one being the SSR). The objective function (Equation 1) minimizes the sum of the variable production costs ($cp_{it}p_{it}$), the inventory holding cost ($cq_{it}q_{it}$) and the set-up costs ($cy_{it}y_{it}$) for all vehicles over the planning horizon of $T = 50$ weeks. Hence, for all vehicles produced over all time periods, the model attempts to minimize the cost of producing a vehicle, holding a vehicle in inventory, and changing over the production system between vehicle batches.

3.5.4 Constraints

Constraint sets play a key role in determining what values can be assumed by the decision variables, and what sort of objective value can be attained. Constraints reflect real-world limits on production capacity, market demand, or available funds, for example. In order to enable the Halo optimization model to produce a realistic and feasible output, the following constraint set is needed:

$$q_{i,t-1} + p_{it} - q_{it} = d_{it} \quad \forall i,t \quad \text{Equation 2}$$

Equation (2) is a set of inventory balance constraints that equate the supply of a vehicle in a time period with its demand for that period. In any period, the supply for an item is the inventory quantity from the prior period $q_{i,t-1}$, plus the production in the period p_{it} . This supply can be used to meet the demand in period d_{it} or it can be held in finished-goods inventory as q_{it} . Since the inventory is required to be non-negative, these constraints ensure that demand is satisfied for each vehicle in each time period. The model permits the input of the initial inventory for each vehicle, q_{i0}

$$\sum_{i=1}^I a_{i1}p_{it} + a_{i2}y_{it} \leq b_{it} \quad \forall t \quad \text{Equation 3}$$

Equation (3) becomes a set of resource constraint equations that reflect the production resource consumption due to both the production quantity of each vehicle and the set-up of

each vehicle model. The production of one unit of vehicle i consumes a_{i1} unit of the shared production resource, and the set-up requires a_{i2} units.

$$p_{it} \leq B y_{it} \quad \forall i, t \quad \text{Equation 4}$$

The constraint sets in equation (4) are the forcing constraints. These constraints relate the production variables to the set-up variables. For each vehicle and each time period, if there is no set-up ($y_{it} = 0$), then this constraint ensures that there can be no production ($p_{it} = 0$) of that Halo model. Conversely, if there is production in a period ($p_{it} > 0$), then there must also be a set-up ($y_{it} = 1$). In (4), B is a large positive constant that exceeds the maximum possible value for all production in a time period, p_{it} . In this model, B is the sum of all demand.

$$p_{it}, q_{it} \geq 0 \quad \text{and} \quad y_{it} = 0, 1 \quad \forall i, t \quad \text{Equation 5}$$

The multiple mathematical expressions denoted by equation (5) ensure the production and inventory variables are non-negative and that the binary set-up variable has only values of 0 or 1. Furthermore, the model has initial conditions that no production has occurred until the system initiates production, $p_{i0} = 0$ at time $t = 0$.

3.5.5 Modeling Assumptions

The model makes a number of assumptions for simplification and to reflect real world conditions:

- There are multiple vehicles to produce, each with independent demand.
- The production of all vehicles utilizes a single shared resource. In the case at hand it is production capacity, which involves a single fixed manufacturing line, its equipment and operators.
- Production costs are linear with the exception of changeover costs.
- The model uses “big bucket”¹⁷ time periods, i.e. multiple vehicles are produced within a time period, in this case, weeks.
- All costs are linear, except for set-up costs due to the binary variable used to determine whether or not a set-up occurs in a time period.

¹⁷ In big bucket time periods one has to worry about how to schedule or sequence the production runs assigned to the time period.

- The models run with vehicular production output in a predetermined sequence, i.e., the build order is SSR → H2 → H3 → H4 and not a random order such as SSR → H4 → H3 → SSR → H2 → H3...and so on.
- It is acceptable to build inventory of a Halo model during one production time period and to hold it to meet demand in a future time period.
- Minimum batch size is determined by containerization strategy, i.e. make batch sizes a multiple of 30 as recommended in Section 2.3.3.
- The maximum batch size is $776/N$, where $N=1, 2, 3, 4$ is the number of Halo vehicles in the production system¹⁸. With a total weekly production capacity of 776 for four vehicles in the system, this ensures that each model will be produced at least once per week, a constraint that can be relaxed as required.

3.5.6 Modeling Optimization Engine Required

As a result of the formulation, the model has 600 decision variables: 200 production variables (p_{it}) for the four Halo vehicles over the 50-week time period, 200 inventory variables (q_{it}) for the four vehicles in each of the 50 weeks, and 200 binary decision variables (y_{it}) denoting whether or not a set up occurs to produce each of the four vehicles during each of the 50 weeks. However, these binary decision variables now complicate the model and transform it from a linear program to a mixed-integer programming (MIP), which requires more computing memory and solution time to solve.¹⁹ An important special MIP case is a decision variable x_j that is an integer with $0 \leq x_j \leq 1$. This forces x_j to take on a value of either 0 or 1 at the solution. Binary decision variables can be used to model *yes/no* decisions; in the case of this model, whether or not a changeover should occur in a specified time period.

Because of the large number of decision variables, traditional solver-type²⁰ software packages are unable to successfully run the model. Most standard solver engines can only handle approximately 200 decision variables in a typical linear program. Therefore, an optimization

¹⁸ The 776 units per week are obtained from a run rate of 9.7 jobs per hour × 40 production hours per week per shift × 2 shifts.

¹⁹ A MIP problem is one where some of the decision variables are constrained to have only integer values (i.e. whole numbers such as -1, 0, 1, 2, etc.) at the optimal solution.

²⁰ *Solver* is a basic optimization engine embedded in the Microsoft Excel product.

engine with greater computational “horsepower” was needed to handle this mixed integer problem. Frontline Systems’ *Premium Solver* was chosen as the optimization engine since it can solve linear, quadratic and mixed-integer programming problems having as many as 2,000 variables. The computing capability of this software package effectively meets the requirements of the Halo optimization model. Even with the additional computational power, running the model under full production conditions of four Halo vehicles consumes multiple hours per run.

3.6 Model Set-Up

Prior to running the model, a number of input variables need to be defined and constraints needed to be established. The following is the baseline list of input and constraint parameters for the model. It should be noted that the input variables with monetary values have been modified from their actual value in order to maintain the financial confidentiality of GM.

Input Parameters

$a_{SSR,1} = 1$	Amount of production resource (capacity) required per unit of SSR production
$a_{Halo2,1} = 1$	Amount of production resource (capacity) required per unit of Halo2 production
$a_{Halo3,1} = 1$	Amount of production resource (capacity) required per unit of Halo3 production
$a_{Halo4,1} = 1$	Amount of production resource (capacity) required per unit of Halo4 production
$a_{SSR,2} = 5$	Amount of production resource (capacity) required for set-up of SSR production
$a_{Halo2,2} = 5$	Amount of production resource (capacity) required for set-up of Halo2 production
$a_{Halo3,2} = 5$	Amount of production resource (capacity) required for set-up of Halo3 production
$a_{Halo4,2} = 5$	Amount of production resource (capacity) required for set-up of Halo4 production
$d_{SSR,t} = 200$	Demand for SSR in time period t (per week and set as a constant in all weeks)
$d_{Halo2,t} = 150$	Demand for Halo2 in time period t (per week and set as a constant in all weeks)
$d_{Halo3,t} = 0$	Demand for Halo3 in time period t (per week)
$d_{Halo4,t} = 0$	Demand for Halo4 in time period t (per week)

$cp_{it} = \$15,000$ Unit variable cost of production for vehicle i in time period t (initially assume unit variable costs are the same for all vehicles) The unit variable cost of production is the sum of material and labor costs for each vehicle.

$cq_{it} = \$250$ Unit inventory holding cost for vehicle i in time period t (initially assumption that the unit variable costs are the same for all vehicles). The unit inventory holding cost of production is the cost to hold one completed vehicle in inventory during time period t .

$cy_{it} = \$1,000$ Set-up cost for production for vehicle i in time period t (initially assumption that the unit variable costs are the same for all vehicles). The set-up cost per changeover is defined as the labor and indirect material cost required to perform a changeover from one model to another.

Constraints

$b_1 = 388$ Weekly production capacity on first shift, where 388 units/week are obtained from a run rate of 9.7 jobs per hour multiplied by 40 production hours per week.

$b_2 = 0$ Weekly production capacity on second shift; no second shift production at initial start up conditions.

$p_{it(min)} = 90$ Minimum batch size. A primary goal of the manufacturing strategy is to minimize the disruption to the plant. To that end, the Halo manufacturing strategy team recommended that, at most, there be only one product changeover per shift. Since the maximum straight production on one shift is 77.6 vehicles (9.7 net while running \times 8 hour shift), and the desired containerization strategy recommends batch sizes of 30, the minimum batch size to satisfy the requirement of no more than one changeover per shift is 90.

3.7 Model Output

A unique feature of this optimization model is that the output of the objective function is an actual cost measure with real physical meaning. In many optimization models, the objective function is simply a combination of a number of factors artificially grouped together to either

minimize or maximize an equation; it has no physical representation. In this model, the production cost output cell is the summation of the combined minimization of three matrices: the production matrix sum, the inventory matrix sum and the set-up matrix sum.

Based on sample inputs, partial output matrices are depicted in Figures 3-3 and 3-4. For illustrative purposes these figures display 18 weeks out of the 50 total weeks calculated. In this case of two vehicles in the system, the output is a production schedule defined by the quantity of vehicles to be produced in each week (Figure 3-3), and a changeover schedule defining the number of changeovers to occur for each model in each week (Figure 3-4).

Production Matrix (Pit)

week	SSR	Halo2	H3	H4
1	240	150	0	0
2	240	150	0	0
3	240	150	0	0
4	90	300	0	0
5	395	0	0	0
6	0	395	0	0
7	395	0	0	0
8	0	395	0	0
9	395	0	0	0
10	390	0	0	0
11	0	395	0	0
12	395	0	0	0
13	0	395	0	0
14	395	0	0	0
15	0	395	0	0
16	395	0	0	0
17	0	275	0	0
18	395	0	0	0

■ ■ ■ ■ ■
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Figure 3-3. Production Output Matrix

Binary Set-Up Matrix (Yit)

week	SSR	Halo2	H3	H4
1	1	1	0	0
2	1	1	0	0
3	1	1	0	0
4	1	1	0	0
5	1	0	0	0
6	0	1	0	0
7	1	0	0	0
8	0	1	0	0
9	1	0	0	0
10	1	0	0	0
11	0	1	0	0
12	1	0	0	0
13	0	1	0	0
14	1	0	0	0
15	0	1	0	0
16	1	0	0	0
17	0	1	0	0
18	1	0	0	0

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Figure 3-4. Binary Set-up Matrix for Changeovers

3.8 Scenario Analysis

Scenario analysis allows the user of the model to specify various boundary conditions and then to evaluate outputs that fall between those conditions. The optimization model was used to run a number of scenarios under different operating parameters and set-ups. Three scenarios, a base case and two alternative production cases, were analyzed in detail, beginning with model validation via the base case. Each of the three cases listed in the Table 3-1 below are now analyzed in detail.

Scenario 1	<i>Baseline scenarios for 2, 3 and 4 vehicles in the system.</i>
Scenario 2	<i>Decreasing changeover time in 6-minute intervals from 30 minutes down to 1 minute.</i>
Scenario 3	<i>Permitting different changeover times for different Halo models.</i>

Table 3-1. Model Scenarios for Evaluation

Scenario 1 — Baseline Scenarios for 2, 3 and 4 Vehicles in the System

The first scenario involved two vehicles in the system with the baseline parameters described in Section 3.6. The demand for each vehicle is held constant at 200 units per model per week (10,000 units annually ÷ 50 production weeks). With two vehicles, the production matrix yields rather basic results, since the model output calls for mirroring the requested weekly demand to produce 200 units of each model in each week. The same result occurs for three and four vehicles in the system because the \$250 per unit inventory holding cost prevents the model from overbuilding in one time period to meet demand in a future time period. Reducing the inventory holding cost per unit to \$175 and then to \$100 still generates the same results. As inventory holding cost drops below \$75 per unit however, interesting results occur (See *Appendix E – Model Output* for complete output results). The model begins to produce models in one week and “banks” them in inventory to sell in a future week. It is possible that the inventory holding cost per unit could drop to almost zero in the Halo program if the assumption is made that due to the artificially constrained supply, demand will always greatly outstrip supply in any time period. In other words, whatever GM builds, it can sell (within reason) and will not be charged a holding cost penalty.

Scenario 2 — Decreasing Changeover Time from 30 Minutes to 1 Minute

It is anticipated that the output of the production system will respond positively to a reduction in changeover time. This should be obvious, since the longer the time required to change equipment and tooling, the greater is the cost penalty in the model. However, the level of sensitivity of the production system is unknown. To evaluate the sensitivity of the model to changeover time, the set up times for each vehicle were varied in the a_{i2} matrix shown in Figure 3-5. The system is evaluated for four models in full production, with demand at 200 of each model per week, yielding a total annual volume of 40,000 Halo vehicles.

A_{i2}	amount of resources required for set-up of item i			
	SSR	Halo2	H3	H4
1	5.00	5.00	5.00	5.00

Figure 3-5. Amount of Production Resources Needed Per Model Changeover

The baseline case assumes that all models require the same amount of production resources to changeover. For this investigation, that assumption is maintained, but the number of production resources is reduced from the 30-minute equivalent, i.e., 5 vehicles, down to one minute, i.e., changeover in less than one vehicle. Since the cycle time of each station is approximately 6 minutes, rerunning the model for these cases yields noteworthy results. These results are presented in Table 3-2. Note that for GM financial confidentiality reasons, the actual model output is disguised as α , β and γ , denoting inventory holding, changeover and total production costs, respectively. The cost outputs for each of the changeover scenarios are then displayed as a percentage of these baseline values.

From Table 3-2, it is evident that a reduction in the amount of resources required to perform a set up has a significant and direct impact on the number of changeovers performed as well as the total production cost. Particularly noteworthy, is the fact that the changeover cost decreases by approximately 88%, and that the number of changeovers increases dramatically by nearly 225%. Therefore, the model effectively “buys” flexibility and adds additional lower-cost changeovers to meet the order-to-delivery requirements without inventorying a large number of units.

Changeover Time	Min. Batch Size	Max. Batch Size	Total # Units Inventoried in the system	Inventory Holding Costs	# of Changeovers	Changeover Costs	Total Production Cost
30 minutes (5 vehicles)	172 units	840 units	30,665	α (baseline)	87	β (baseline)	γ (baseline)
24 minutes (4 vehicles)	163 units	839 units	28,218	$\alpha \times .93$	96	$\beta \times .82$	$\gamma \times .98$
18 minutes (3 vehicles)	166 units	838 units	27,894	$\alpha \times .91$	103	$\beta \times .66$	$\gamma \times .95$
12 minutes (2 vehicles)	142 units	462 units	16,863	$\alpha \times .55$	122	$\beta \times .48$	$\gamma \times .93$
6 minutes (1 vehicle)	131 units	456 units	16,384	$\alpha \times .51$	131	$\beta \times .24$	$\gamma \times .91$
1 minute (< 1 vehicle)	105 units	450 units	4,872	$\alpha \times .12$	196	$\beta \times .03$	$\gamma \times .88$

Table 3-2. Maximum Batch Size and Production Cost as a Function of Changeover Time

Scenario 3 — Permitting Dissimilar Changeover Times for Each Halo Model

Still another interesting factor warranting further investigation is the effect of maintaining different changeover times for different Halo models. Table 3-3 shows the potential variability in times for four proposed changeover scenarios.

Changeover Architecture	
From $\alpha \rightarrow \beta$	Changeover Time
BOF \rightarrow BFI	w minutes
BOF \rightarrow BOF	x minutes
BFI \rightarrow BOF	y minutes
BFI \rightarrow BFI	z minutes

Table 3-3. Architecture Changeover Scenarios

If different changeover times do indeed exist, then there is some variation in the changeover process between architectures and models. This variation should be minimized to reduce the changeover downtime impact to the factory and to help maintain standardized processes. An evaluation of the effects of the variation in changeover times involved running one scenario at extreme ends of changeover spectrum, i.e., it takes only 6 minutes to changeover from one BOF vehicle to another but it takes 30 minutes (5 vehicles) to changeover from a BOF vehicle to a BFI vehicle and vice versa. Running these scenarios, the model reveals that many more changeovers are allowed for products with low changeover times than for those with large changeover times. The baselines in this case are the vehicles requiring 30-minute changeovers, using up 5 units of production capacity. The units requiring only 6 minutes, or 1 lost unit of production, to changeover are compared to the baselines on a percentage basis. The model demonstrates again that total inventory holding costs and changeover costs decrease significantly as the amount of production resource required to perform a changeover decreases. These results are summarized in the Table 3-4.

Model	Changeover time from previously running model	Inventory Holding Costs	# of Changeovers	Changeover Costs	Total Production Cost
SSR (BOF)	6 minutes	$\alpha \times .55$	210	$\beta \times .21$	$\gamma \times .78$
Halo2 (BFI)	30 minutes	α (baseline)	76	β (baseline)	γ (baseline)
Halo3 (BFI)	30 minutes	α (baseline)	76	β (baseline)	γ (baseline)
Halo4 (BOF)	6 minutes	$\alpha \times .55$	210	$\beta \times .21$	$\gamma \times .78$

Table 3-4. Scenario Results for Architectures with Varied Changeover Times

These three modeling scenarios described above provide insight into the workings of the model and the sensitivity of the production system to key parameters. It is evident from the analysis performed that the variable with the greatest impact on overall production output is the amount of production resources consumed to perform a changeover. Although other variables such as inventory holding costs and production cost per unit have an effect on the model, they cannot be changed as readily in the real world system. Therefore, to affect change in the Halo system, the engineering and operations teams must strive to reduce changeover cycle time.

3.9 Discrete Event Simulation Based on Model Output

As a result of the model output, a number of observations were made. First, it is evident that in order to minimize set-ups, some amount of product inventory is built ahead and held until some future demand period. However, since the plan is to artificially constrain the supply of the Halo vehicles at approximately 10,000, units it is possible that GM can sell any excess inventory of vehicles produced in the time period that they are produced. This will have a negative impact on order-to-delivery requirements if there are large numbers of vehicles built to order instead of being built to stock.

Second, after many runs at different volumes, it appears that the range of acceptable batch sizes to meet annual demand of 10,000 units per model is between 90 and approximately 850. In this range, minimum production costs are achieved by running a vehicle model as long as possible, therefore using large batch sizes. Smaller batch sizes can be used as changeover time is reduced, as previously demonstrated in Table 3-2.

As a result of these findings, the Halo manufacturing strategy team would like to evaluate the actual production factory using different batch size conditions. However, since the LCC is not yet ready to run production, the team cannot conduct actual production to test scenarios. Instead, the findings gained from the model are fed into a discrete event simulation software package that enables evaluation of the actual station-by-station throughput of the Lansing Craft Center. The computer application used to run the simulations is Rockwell Software's *Arena Systems Modeling* package. Such simulation programs can be used to model the flow or movement of entities within a system. They have been used to model assembly lines in factories, the movement of people in airports, workflow in organizations, and cash flow in economies. The benefit of these types of programs is that they can be used to model or simulate anything that moves or is transported in a network.

The purpose of these discrete event simulations is to model each station in the factory as an interaction between deterministic and stochastic elements, and to feed the output of the linear programming optimization model into simulation software to evaluate potential factory issues. An example of the simulation model set-up for the general assembly factory is presented in Figure 3-6. The simulations were run to evaluate throughput for critical areas of the manufacturing process, including:

- *Paint Factory* - Rework and respot vehicles stuck in a loop
- *General Assembly Paint Bank* - Capability of multi-lane buffer to handle paint stragglers
- *General Assembly Main Line* - Ability to reallocate labor based on vehicle content

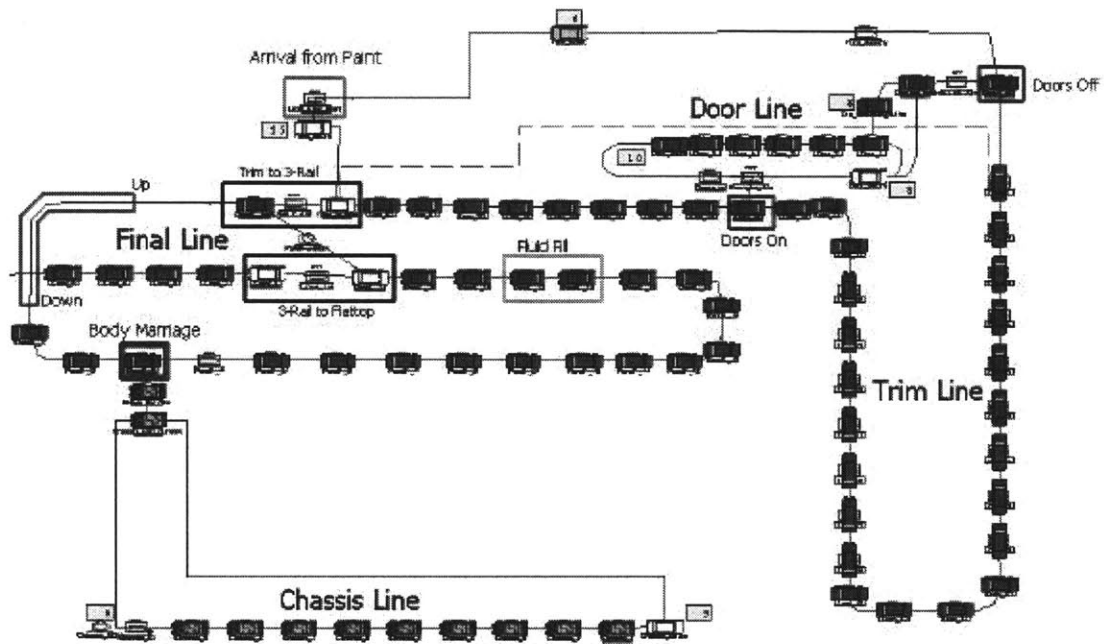


Figure 3-6. General Assembly Discrete Event Simulation Using ARENA

The results of the general assembly simulation were then utilized to discover constraints in the production system and validate proposed batch build strategy. A number of key issues were discovered as a result of running the general assembly simulations. Further analysis of these issues led to recommendations and potential solutions for the factory simulation, as follows:

- The factory cannot reallocate labor based on a dynamic changeover due to BOF versus BFI differences. Thus, although it would be helpful to move operators from the chassis line to the trim line to compensate for the differences in required labor hours per model between the two types of vehicles, it cannot be done. As a result, it is recommended that for future Halo vehicles, the development team attempt to match labor content of the new product to the designed LCC plant capability. Minimizing differences in vehicle content will help to further this goal.
- If the factory wants to reallocate labor as a result of processing differences between each model's required labor hours per product, one option is to run the chassis line and

the main line in an asynchronous mode. In this mode, the chassis line would operate at a slightly faster run rate than the main line and gradually build up a WIP of assembled chassis to feed the main line. The chassis line run rate must be timed such that when the changeover bubble hits the trim line, chassis operators will have completed their process tasks and are able to move to the main line to assist with assembly tasks. The benefit of such a system is that it allows for better labor allocation and balancing between various types of vehicles. However, this advantage comes at the price of increased WIP and material floorspace to store completed chassis.

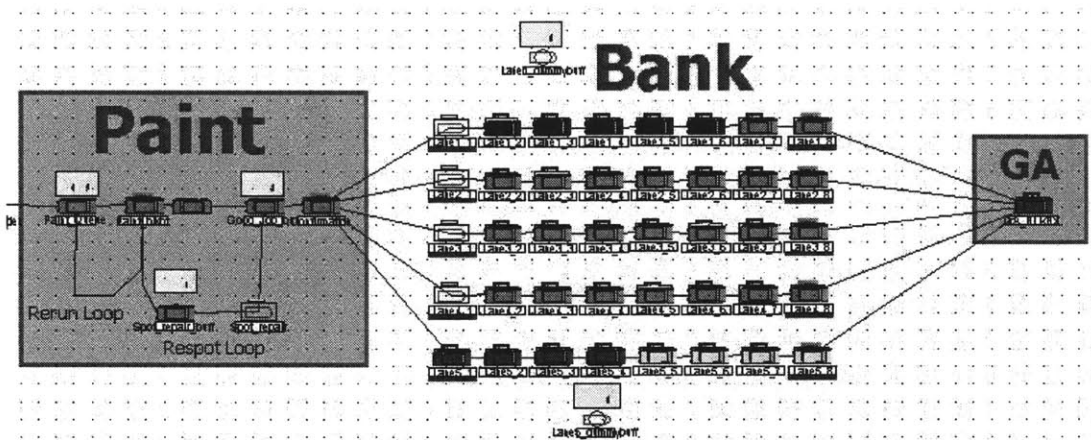


Figure 3-7. Body Buffer Between Paint and General Assembly Factories

Another key area of the factory analyzed by the simulation is the buffer between the paint and general Assembly sub-factories, as seen in Figure 3-7. This buffer is needed to store built up WIP in order to provide a time delay for a vehicle coming out of the paint factory so that the necessary components can be ordered and reach the general assembly factory when the vehicle body hits the line. Additionally, the WIP buffer ensures that the general assembly factory never runs out of vehicle bodies. Since GA is the factory where the completed vehicle is produced, any downtime due to lack of available painted bodies results in fewer vehicles being shipped out the door, obviously an unacceptable situation for an automotive plant. There are six lanes in the buffer, but one lane must be used as a return lane for underbody skids. In the simulations, the system was analyzed as both a 4-lane and 5-lane buffer, with different numbers of models in the system. Key points from the paint bank simulation are:

For **4 lanes of 10 jobs** each:

- With two vehicles in the system, a one-straggler lane for each product, and two middle lanes for current product, buffer capacity is sufficient to support 9.7 jobs per hour.
- With three vehicles in the system, a one-straggler lane overflows bank capacity approximately 10% of the time, irrespective of batch size.
- With four vehicles in the system, a one-straggler lane overflows bank capacity approximately 25% of the time, regardless of batch size.
- Simulation of this scenario shows that four lanes of 10 jobs each is not a workable solution for the paint bank to meet overall Halo Program goals.

For **5 lanes of 8 jobs** each:

- With two vehicles in the system, two lanes dedicated to each product, and the middle lane open to current production, stragglers do not overflow their dedicated lanes.
- With four vehicles in the system, one dedicated lane per product and the middle lane open to current production, stragglers do not significantly overflow their dedicated lanes. However, one lane for current production is insufficient to keep up with the number of vehicles required by the broadcast window.²¹
- This simulation shows that although 5 lanes do not overflow, 2 lanes for production is not sufficient for the number of vehicles in the broadcast window. Therefore, there is a significant need to investigate the possibility of using the sixth lane for production, even though it is currently utilized as a skid return lane. Six lanes of 8 jobs each is a feasible option for paint buffer utilization for Halo vehicles running at the same time.

3.10 Modeling Issues

The linear program optimization model is useful for assisting with planning decisions and strategy formulation. However, the model has its limitations, and the user should be aware of them. The following are some of the problems it presents:

²¹ The broadcast window is the point where the vehicle body coming out of the paint factory gets scheduled into the general assembly factory. At this point an order is triggered for the components needed to complete the vehicle through the general assembly factory.

- The biggest implementation issue encountered is that the model does not allow more than one changeover per vehicle per week as seen in *Figure 3-4*. Since all the decision variables in this matrix are binary, the model constrains the number of changeovers in a time period to either be zero or one. With the maximum of four Halo models in the system, this limitation is not as severe, since one goal of the system is to not changeover more than once per shift. But with fewer models running, the model may not output the true number of optimum set-ups if that number is greater than one. Although it seems trivial to change the binary decision variable to an integer decision variable, it expands the complexity of the model many-fold. Even the Premium Solver software cannot solve such a mixed-integer model with 600 decision variables. An option for handling this matter is to change all the binary variables to integer variables and to only run model for a period of three months or one quarter of the production calendar. Assuming the input demand and model output reach steady state in that time period, the results obtained in the three-month time period could be extrapolated to determine the entire year's production schedule.
- The linear program limits the order in which models are run to a fixed sequence, as mentioned in Section 3.3.5. This imposed sequence artificially constrains the production system and does not allow for potential out-of-sequence manufacturing scenarios. This issue could potentially be alleviated by changing to some larger super-sequence, e.g., build SSR → H3 → H4 → H2 → SSR → H3 → H4, and then repeat it. But the added complexity of the number of possible combinations makes it extremely difficult to further investigate an optimal solution in any meaningful manner.
- Mathematical models are only as useful as the data input, and this certainly applies in this case. Since the Halo program is still under development and the production facility has not been set-up or validated, much of the data on changeover times, changeover cost, line run rates, and throughput are still somewhat speculative at this stage. Once the launch of the SSR draws nearer, more of the relevant input data in the model will be available and validated.

3.11 Extensions to the Model

Addition of Production Learning Curve Effects

Since the model output varies the number of units, and therefore, the amount of time between production runs of a single Halo model, the ability to assess the impact of the start-up learning curve for each model changeover would be helpful. Enabling model output based on input constraints established from historical plant downtime and restart data would make the model more closely resemble real world conditions. In this manner, the model would permit investigation of the sensitivity of production learning to batch size and changeover frequency. Production learning will be discussed in more detail in the following chapter.

Change Time Periods From Fixed to Variable

The time period in the model is currently fixed in units of weeks, which forces the model's production output to fall in cycles of weeks. An alternative formulation would be to create a decision variable t_n for each of the Halo vehicles that determines the optimal time to produce each model in each batch. The benefit is that it allows the model to determine how frequently to produce each vehicle. For example, instead of producing 270 SSRs in week number 10, the model could produce 180 SSRs over any 3-day period. With this type of formulation, the number of decision variables in the model now grows to over 2,000 making it even more difficult and time consuming to solve.

Modify Objective Function to be Profit Maximization

Although the objective function in this model is *production cost minimization*, an alternative formulation could be *profit maximization*. The overall results are expected to be similar, but using profit maximization may have enabled a broader scope of variables to more accurately represent the overall Halo system. Furthermore, although cost reduction is certainly worthwhile, it is often better to know how much can be *made*, in comparison with how much can be *saved*. However, performing a profit maximization evaluation is more complicated, since the modeler needs to know a multitude of other related costs as well as the price-sales relationship for each vehicle model.

3.12 Summary

The deliverables produced during the development and analysis of the optimization model include defining the model scope, creating a working linear programming model, and analyzing sensitivity of the model and production system to a various input parameters.

Although the model has its share of technical and input parameter issues, developing the model has produced several fundamental benefits. The first is an increased understanding of the capability of the overall Halo production system. The project originally began with a broad problem statement, *what is the optimal manufacturing strategy?* But as the understanding of the problem increased, the direction of the research was modified, now focusing on more specific areas. A model scope was created to give the project a feasible boundary. Working on the model also enabled identification of what data are required to produce better output, such as the need for validated input data and the inclusion of learning curve effects, described in Chapter 4.

Another benefit of creating the model was that the increased understanding of the manufacturing challenges faced in specific areas can be used help focus future batch build efforts. Performing discrete event simulations using inputs from the optimization model permitted more detailed evaluation of critical areas in the production process. The next step in the analysis is applying the learning from the model and the simulations to help the Halo manufacturing strategy team determine how to address the primary issues identified for the program.

Finally, research and data collection for the model underscored some of the organizational and cultural issues that are likely to arise as a result of implementing the batch build production system. With the implementation of this new system, the production, engineering and management groups involved with the Halo program must address operational issues they have never previously experienced. It is this final point that leads to the discussion in the next chapter of socio-technical issues surrounding batch build manufacturing.

Chapter 4 – Socio-Technical Issues with Batch Building

4.1 Organizational and Cultural Issues with Batch Build Manufacturing

Since batch build manufacturing is a novel method of doing business at GM and, in many ways, is not consistent with GM's high volume assembly plant operations thinking, several social and technical issues arise. In this section, a number of the cultural and organizational questions that might surface in the GM plant as a consequence of the proposed manufacturing strategy are considered.

4.1.1 *Effects of Learning as a Function of Elapsed Time Between Batch Runs*

A productivity-influencing effect with which both the LCC and high-volume mixed production plants do not have to significantly contend, is the effect of *production learning*. For example, currently the LCC only builds cars of a single model and does not deal with platform or architecture changeovers. Therefore, the learning curve effects come into play only minimally after the plant is off-line for a holiday or planned shutdown and has to restart production. Similarly, a high-volume mixed production plant essentially switches between vehicles “on-the-fly” and does not incur production learning losses because the operators are continually assembling each of the many multiple models every day. Additionally, the operator's work content per station is small and relatively easy to remember. On the other hand, the Halo program presents a unique challenge with respect to learning curve effects. Since multiple models will be produced from very different platforms and architectures with varied assembly procedures and sequences, a certain amount of *forgetting* and *relearning* will occur each time the factory cycles through a batch sequence. This forgetting and relearning process leads to some level of *production loss* with each model changeover.²²

On a typical high volume general assembly line, the overall assembly tasks are spread among over 70 stations. With a cycle time of approximately 30 seconds to one minute, operators on the high-volume line are only given responsibility for a few assembly tasks at their station. In the Halo batch build system, all the tasks required to completely assemble a car are now

²² Production loss is defined as a degradation of production output, either in quality or productivity.

divided among approximately 25 stations due to the shortened line length predicated by the smaller factory. This leads to assembly times that are close to 6 minutes with more than 10 tasks at some stations. These added tasks exacerbate the forgetting and relearning effects.

For example, if the LCC builds SSR models in a batch of 210 units on one shift over the course of three days and then cycles to Halo2, Halo3 and Halo4 for approximately 3 to 5 days for each model, by the time the SSR is produced again, nearly two weeks will have elapsed. *How does this elapsed time between production runs of the same vehicle model affect the manufacturing operation?* It is proposed in Figure 4-1 that if batch sizes are small, on the order of 10 vehicles or less, then the production loss is small, since the operators cycle through models frequently and the forgetting effects are minimal. Moreover, studies have demonstrated (Rachamadugu, 1995) that the relearning time for automotive assembly operators is short when cycle times for assembly processes are maintained at less than approximately one-minute. This is due to the fact that as the number of tasks increases, the opportunity to forget a single task within the complete set of tasks likewise increases. Therefore, as batch sizes increase to between 100 and 1,000 units, the forgetting effect has a greater influence on the assembly process, and the production loss increases. Eventually, as batch sizes become very large, over 1,000 units, production loss flattens off and becomes constant because essentially, an individual cannot forget to any greater extent.

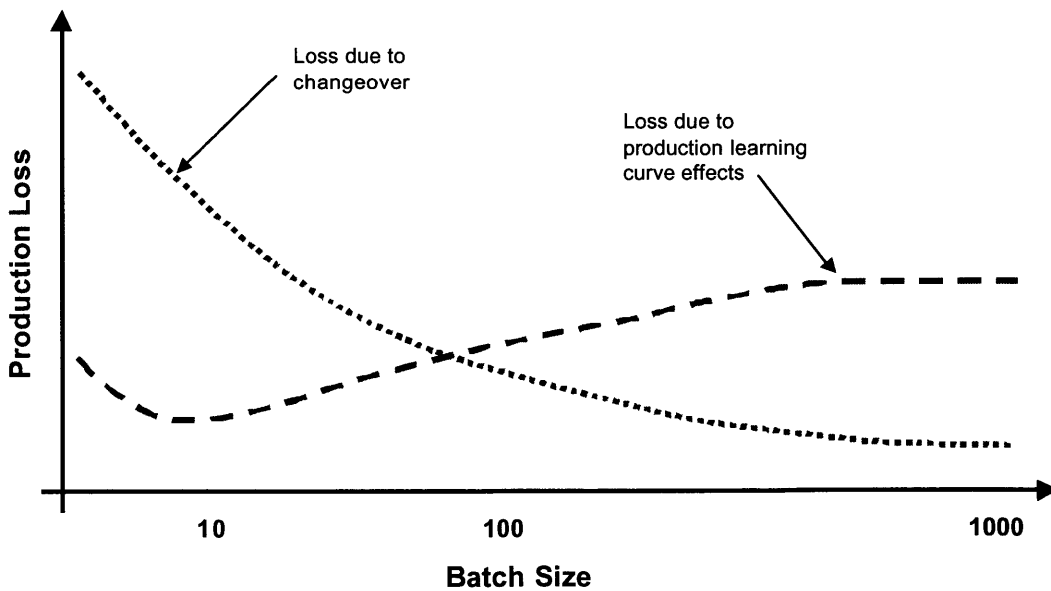


Figure 4-1. Production Loss as a Function of Batch Size

A second driver of production loss is the loss due to changeover, described earlier. This loss is greatest when batch sizes are very small, since frequent changeover incurs both the physical cost of the set-up (e.g. salaries for skilled-tradesmen, tools, indirect material) and the cost of lost vehicles due to production downtime. As batch sizes become large, this production loss is eventually minimized, and for an infinitely large batch, reaches an asymptote of zero.

A future extension of this thesis investigation is to incorporate production forgetting and learning curve effects into the batch size optimization model. A highly beneficial extension of the base model is the ability to simulate the impact of a start-up learning curve for each model changeover. In order to do this, plant downtime and restart data are being collected to create a mathematical expression for operator performance level as a function of *forgetting*, *learning* and *batch size*. The author theorizes that the results of such a study might appear as the Laplace transforms seen in Figure 4-2. In this figure, the rise constant (ω) illustrates that learning occurs rapidly and reaches a maximum value of performance quickly (equal to 1), while the decay constant (ν) illustrates that forgetting occurs gradually and it takes time for performance level to drop off. An extension of the model is to calculate the coefficients of the Laplace transform based on existing plant downtime and restart data, and include them with the appropriate equations as a function in the optimization model.

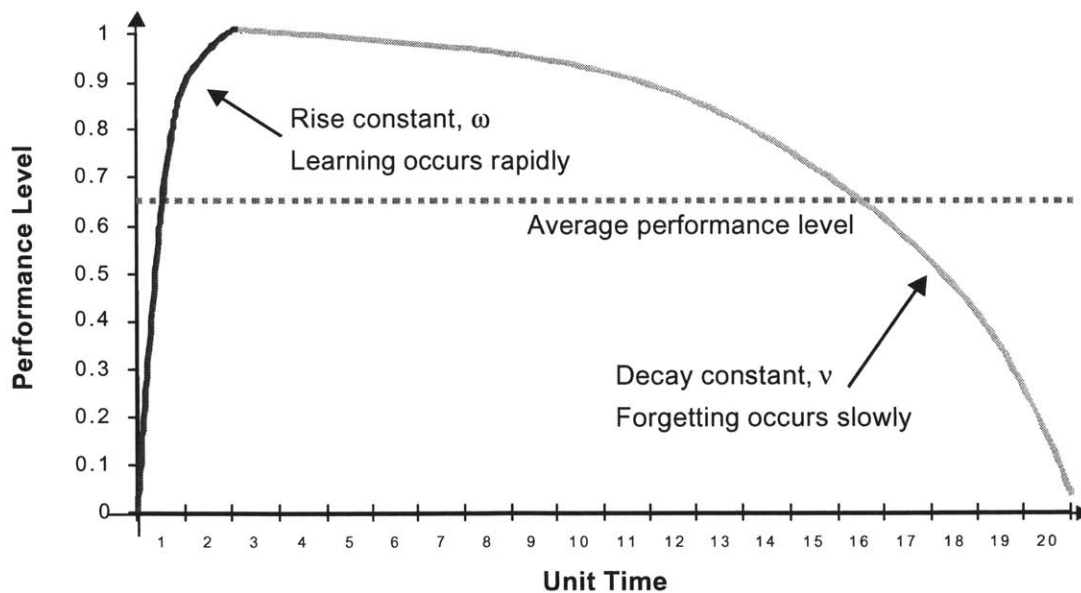


Figure 4-2. Effects of Learning and Forgetting on Performance Level

Based on this type of effect, there are a number of ways to handle production learning in the Lansing Craft Center.

1. *Maintain a constant line speed* – This option will maintain a constant run rate and productivity level, but it creates the potential to incur quality impact due to the forgetting and relearning effects. Since there is no special verification of the quality level of the initial vehicles in a new batch, the potential for escaping quality defects exists.
2. *Slow the line speed and verify initial units from each batch* – This option will decrease plant productivity, but it attempts to ensure the quality level of units produced immediately after the changeover. The benefit is increased quality, but the detriment is diminished productivity and hence increased cost.
3. *Maintain the same operator at the same station* – This option will decrease flexibility within the production system to move operators where needed, but it allows workers at each station to become experts at their assembly tasks. For example, keeping the same operator at the instrument panel installation station will make that operator an expert at that process. The instrument panel installer then becomes an instrument panel installer expert for all Halo vehicles, irrespective of model-specific details. Maintaining this operator consistency will help reduce changeover start-up and learning curve effects.
4. *Utilize existing quality gates in production* – This option will perform specific in-process pass/fail checks as per the normal production standard operating procedure (SOP). However, the amount of time required to perform these checks may be greater for the units manufactured immediately following a model changeover. If the system does not allot sufficient time to perform these verifications, escaping quality defects may result.
5. *Develop line side training material* – Providing instructional videos, assembly diagrams or web-based tutorials will allow the operators to relearn quickly if they want or need a brief refresher on a specific assembly process.

6. *Extend the changeover bubble size for early production runs* – To handle the learning curve associated with the changeover process itself, it is recommended that initially the changeover bubble is made larger than the optimal time required for model conversion. Thus, operators will have sufficient time to changeover tooling and equipment at their station and verify that the changeover has been completed as per the SOP.

4.1.2 Modification of Workforce Job Responsibilities

Implementing batch build manufacturing in the LCC poses potential issues for the distribution of workforce responsibilities. In a traditional GM manufacturing operation, an operator is trained and becomes skilled at one station or a portion of the production line. In the batch build process, operators may have to move from one process to another as needed. Since each operator has a slightly different method for performing a specific process, this variation leads to the issue of “*how tight is tight?*” for certain factory processes.

For example, operators responsible for installing and fastening a wheel and tire assembly to the vehicle have a physically demanding job – they pick the wheel/tire assembly from a rack (either by hand or using a load-assist), move the assembly to the vehicle, align the bolt holes on the wheel over the studs, place lug nuts on the wheel studs, and then fasten the lug nuts as specified using a torque calibrated air-powered lug nut runner. By the sheer nature of this job, the operators working at this process are usually large in stature and physically capable of handling the task at hand. They have a certain method of handling large components and assembling them to the vehicle. On the other hand, operators responsible for hand assembling small electrical connections in the engine compartment have different capabilities that are well suited to their process. In this case, operators may have a smaller stature to be able to access the constrained, difficult to reach areas of the engine bay. They are used to working with small, easily damaged components and handle them in a manner appropriate to the assembly task being performed.

Although the operator descriptions above may be at opposite ends of the spectrum, they illustrate the difficulty that can occur if operators are required to move from one process to

another during model changeovers. Effectively addressing the issue of labor reallocation is paramount to enabling flexibility in the manufacturing system.

4.1.3 Workforce Scheduling Policies as a Function of Batch Build Strategy

General Motors uses the term “base engineered content” (BEC) to allocate a labor standard, or amount of labor required, to assemble a specific part or component. Comparing the differences in BEC between car- and truck-based products highlights the difficulties involved in producing multiple architecture vehicles on the same line. Typically, a truck-based BOF vehicle has greater base engineered content due to a frame that requires separate subassembly processing from the body of the truck. A car-based BFI vehicle requires fewer person-hours of assembly time since more of the vehicle is concentrated around the core unibody structure. This variation is minimal throughout the body and paint factories, but becomes significant in the general assembly factory.

In the general assembly factory, the differences in BEC lead to an unbalanced workflow. Figure 4-3 shows an example of the differences in work content on the chassis assembly line between the SSR and a proposed car-based Halo2 vehicle. The variation in work content between the two architectures of vehicles implies that an over- or under-staffing issue will occur if the same operators are used to run the line for all types of models produced. If, for example, it takes 10 operators to run the chassis line during SSR production and only 7 operators to run the chassis line during Halo2 production (Figure 4-3), the result is a stepped staffing pattern as seen in Figure 4-4.

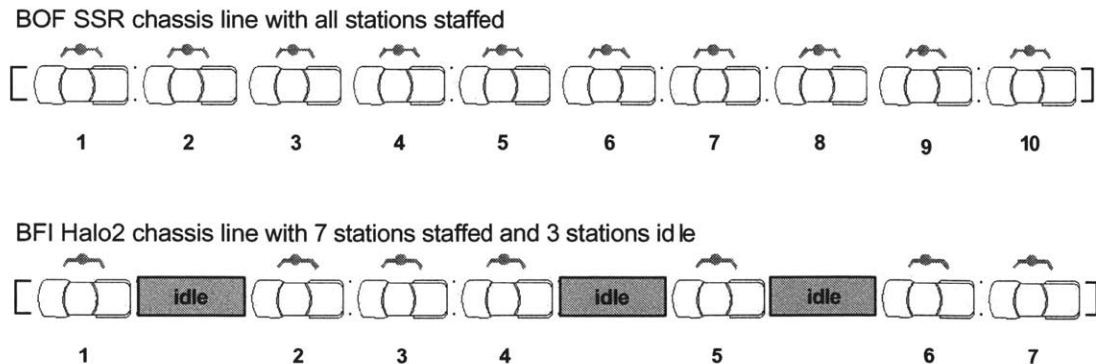


Figure 4-3. BOF vs. BFI Staffing Requirements for Chassis Assembly

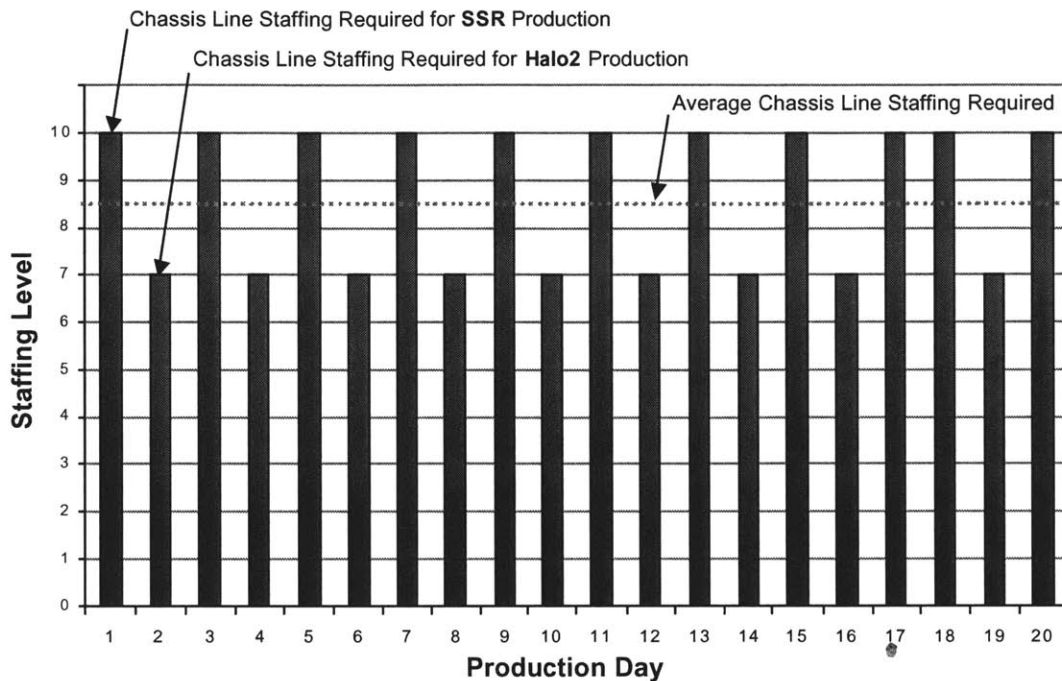


Figure 4-4. Chassis Line Staffing Level as a Function of Architecture

Extending this analysis to the entire general assembly factory, there are number of areas where the variations in BEC cause a staffing imbalance as models changeover. Examining the factory as a whole, it may be possible to address these imbalances by moving operators from one function to another as model changeover occurs. Other methods of line balancing could also be employed, such as utilizing the chassis supplier to perform some of the assembly work prior to shipping the chassis to the LCC. As noted, labor allocation during changeovers is a key to production system flexibility.

4.2 Summary of Chapter 4

This chapter introduces some of the socio-technical issues surround batch building at the Lansing Craft Center. It considers the effects of production learning as a function of batch size and theorizes that the effects become significant when batch sizes are large. After evaluating potential learning curve effects on the plant's output, recommendations are offered that minimize these effects and ensure a smooth transition from batch to batch, even over long production runs.

The chapter also describes the potential modifications to workforce job responsibilities and underscores the difficulty that can occur if operators are required to move from one process to another during model changeovers. Finally, this chapter discusses workforce scheduling policies that arise as a result of the batch build strategy and the tradeoff between maintaining flexibility and the disruptions that can be caused by an unbalanced workflow.

The following chapter concludes this thesis by summarizing the developed batch build strategy and recommended policies. It discusses methods to ready the workforce for a multi-product environment, and addresses further considerations for low-volume niche vehicle manufacturing. Lastly, future utilization of the batch build optimization model by General Motors and the author are considered.

Chapter 5 – Conclusions

5.1 Summary of Recommended Batch Build Policies

This thesis developed a number of strategic recommendations for Halo manufacturing based on interviews with employees from GM and its partner-supplier, participation on the Halo batch build strategy team, tactical evaluation of the factory changeover process, and scenario analysis using a linear programming optimization model and simulation software. To organize these recommendations into a coherent strategy, this section of the thesis summaries all suggested batch build policies under four main areas: 1) *tooling and equipment changeover*, 2) *material changeover*, 3) *product and process complexity reduction*, and 4) *readying the workforce for multiple products*.

5.1.1 Tooling and Equipment Changeover

Analysis of the tooling and equipment changeover shows that overall efficiency of the production system will depend highly on a robust changeover process. Therefore, there are a number of key questions to ask. For example, *how can this process be made as flexible as possible?* while at the same time asking, *is it less costly to have unique sets of this tooling per product or to invest in a flexible system that accommodates all products?* To that end, the following strategies are recommended:

- Create a low volume bill-of-process (BOP)²³ document defining the standards and criteria to establish enablers for producing Halo vehicle tooling.
- Keep tooling as simple as possible using design-for-manufacturing (DFM) and design-for-assembly (DFA) methods for hardware design.
- Design flexible tooling that can be changed over in-place, as opposed to dedicated roll-away tooling that requires factory storage space for each tool set.
- Work to reduce changeover for bottleneck processes throughout the sub-factories.
- Design transport carriers (skids) with flip-up style locating details.
- Design equipment hardware to minimize the tools and skills needed to perform changeover.

²³ GM's "bill of process" (BOP) is discussed in detail on page 76.

- Consider future products and platforms that are yet undefined.
- Attempt to reduce changeover bubble time from 30 minutes to fewer than 10 minutes.

The first recommendation listed for tooling and equipment changeover deserves further explanation. General Motors is an extremely process focused corporation. A result of this process focus is the desire to “run common” by concentrating on common processes, systems and components across the corporation. In GM’s manufacturing operation, a key element of running common while being flexible is a recently implemented program called the global “bill of process” (BOP). The purpose of this strategy is to install common operating, training and material procedures at all plants in order to make it easier to launch new vehicles and move existing ones from plant to plant. Much like the “Copy Exactly” production methodology made famous at Intel, this plan will allow GM’s plants to efficiently move products around as necessary.²⁴ The global BOP has been developed for high volume plants, which make up a majority of GM’s manufacturing operations.

However, the needs of the Halo program are in many ways different than the requirements for a high-volume production. Therefore it is recommended that GM develop a *low-volume BOP* focused specifically on the process, tooling, machinery and equipment requirements needed to “run common” across low-volume Halo products. Additionally, GM must drive product design commonality to readily integrate new Halo vehicles into the low-volume BOP.

5.1.2 Material Changeover

Research for this thesis discovered that in order to develop an efficient manufacturing system, a well thought out material changeover plan must be implemented in conjunction with a robust equipment changeover process. To that end, the following recommendations are offered:

²⁴ To address the differences in product quality from different factories, Intel developed “Copy Exactly”, a process management technique designed to ensure production synergy across all sites. All semiconductor factories producing the same product are identical in every possible respect, unless overwhelming justification for differences exists. This has allowed Intel to create a ‘distributed manufacturing’ system – one large integrated factory with processes physically located in multiple production sites.

- Utilize JIT delivery for most components and subassemblies to minimize required material storage in the LCC.
- Maintain an in-plant buffer for critical items, e.g., roof panels.
- Utilize flexible containers capable of handling the same type of part for multiple vehicle types and models.
- Employ highly modularized product designs so as to minimize the number of parts that must be containerized and stored on the line and to enable rapid completion of the vehicle on the main production line.
- Target batch sizes to full container utilization in the body shop, which leaves racks empty at the end of each batch and ready for return to the supplier.
- Establish the broadcast point for components after bodies leave the paint shop, and allow the general assembly factory to use all the parts on the line within each scheduled batch.
- Sequence parts and subassemblies for the general assembly factory to have parts released to the line only when that vehicle has started through the general assembly factory.
- Create batch sizes that are divisible by 30. Major commodities requiring unique racks can then be shipped in quantities of 1, 2, 3, 5, 6, 10, 15 or 30 per container or rack.
- Utilize kitting of parts and subassemblies where cost-justified.
- Minimize material handling through value stream mapping.
- Match material changeover capability to equipment changeover time to prevent stockouts.

A key area of the material strategy that requires further investigation is the process for defective incoming parts and for parts not used due to a reworked vehicle body that is separated from its assigned batch.

5.1.3 Product and Process Complexity Reduction

Plant complexity can be divided into two types: *product complexity* and *process complexity*. Product complexity exists whenever more than one part number is used for the same application. A case in point is the SSR, where four different colors of interior trim components create product complexity. However, since all trim components install the same way, they create no process complexity. But product complexity creates material handling

issues for the plant. For example, with the SSR, the trim components must be sequenced so that the proper color trim part is installed in a car with a matching exterior color.

Process complexity occurs when the same part or subassembly is installed in a different order or by a different process. For example, building both BOF and BFI architectures on the same line requires that the spare tire will have to be loaded onto the vehicles in two different locations, using two different processes.

It is important that GM considers both product and process complexity as it designs both the Halo vehicle and the manufacturing system needed to produce the vehicles.

5.1.4 Readyng the Workforce for Multiple Products

Training

For a number of years, the Lansing Craft Center has been running a single product through the plant. Therefore, the LCC production staff does not have experience with producing multiple platforms and architectures at the same time. Accordingly, it would be highly beneficial to provide the production operators and plant operations staff with a base level of mixed-model training and experience prior to the introduction of the second Halo vehicle into the LCC. This can be accomplished a number of ways, as follows:

1. Bring operators from the high volume plant that produces the platform for the Halo vehicle into the LCC to train the staff on the new production process.
2. Take operators from the LCC and permit them work in a mixed-model environment, such GM's Moraine Truck Plant²⁵, for a month of training, and then have them return to the LCC for Halo production.
3. Rotate LCC operators with those from a mixed-model plant to allow a larger group to get mixed-model experience. Over time, this will diffuse the multiple-model mindset into the entire LCC workforce.

²⁵ The Moraine Truck Plant builds a trio of sport utility vehicles (SUVs) based off a GM 4-wheel drive truck platform. The SSR is derived from the same platform and thus shares many components with the SUVs in this mixed-model plant.

4. Provide a training opportunity for LCC operators in a GM stamping plant that already runs under a batch production system, to gain experience in batching and changeovers.
5. Begin practicing the changeover process, first in a non-production setting, then on the actual line, so the operators are experienced with performing changeovers before the next Halo is launched into production.
6. Before building production hardware, discuss concept tooling and its planned changeover process with the operators who will use it.

Although the suggestions made above are beneficial in theory, it must be understood that they are extremely difficult to implement in practice. The United Auto Workers union has standard policies and requirements based on a seniority system, which prevent production operators from easily moving from one plant to another, even for training purposes.

Standardized Changeover Procedure

Studies have revealed that the factor that has the greatest impact on changeover time is the establishment of a standardized changeover procedure. Research by Tan (1994) found that to minimize the impact on factory throughput, the implementation of a standardized changeover process is one of the greatest contributors to minimizing changeover downtime problems. The best practices for a changeover at each station must be identified and changeover-process checklists created to support operators in reducing changeover time and variability. Tan's findings also showed that experience and training matter significantly in changeover efficiency.

Furthermore, in order to maximize utilization of the changeover bottleneck process, all employees working on or around the bottleneck should be made well aware of the importance of the constraining process. In this case, the bottleneck welding equipment in the body shop needs to be closely managed in order to minimize changeover downtime and to enable processes promoting rapid changeover. Without a clear vision and execution plan for managing the bottleneck changeover process, the utilization of this equipment will end up being lower than expected.

Lean Quality Systems

A number of lean quality measures can be implemented to assist the factory with minimizing the effects of a changeover and maximizing product quality. Some of the lean processes and systems used to promote product quality that can be applied in the LCC are the following:

- *Standardized Work* – This is a key element to repeatability of the changeover process. Standardized work principles must be taught, implemented and monitored as part of all processes at the LCC, including model changeover. The best practice for each changeover process should be developed into a standard operating procedure (SOP) so that constant tweaking of established processes does not occur on the production floor.
- *Employee Involvement* – Operators should be both empowered and encouraged to develop best processes. Opportunities for employee involvement include DFM and DFA workshops for new tooling and equipment, cross-functional continuous improvement teams, team goal setting, and the ability for a plant employee to stop the build process at any time to ensure quality products are being made.
- *Clearly Defined Processes* – Define the manufacturing processes and changeover process at each station based on the best practice evaluation noted above. Then, clearly document and articulate all processes via SOPs so that all the appropriate personnel in the plant can readily identify and utilize them.
- *Visual Management* – Develop and maintain a visual factory where items that deviate from the established process are readily identifiable. The intent of a visual factory is to set-up the entire workplace with signs, labels, color-coded markings, and the like, such that anyone unfamiliar with the process can, in a matter of minutes, understand the process and readily recognize the difference between the correct process and deviations from the ideal.
- *Error Proofing* – Utilize Failure Modes and Effects Analysis (FEMA) for process design in order to create error detection and mistake-proof processes to ensure a consistent

quality product is manufactured. FEMA is a systematic approach for determining the likely failure modes of a new product or process so that action can be taken early in the development process, at the design stage, in order to minimize or eliminate those failures.

- *Total Predictive Maintenance* – Knowing that unplanned downtime due to the changeover will have a negative impact on the Halo business case, the LCC maintenance team should attempt to minimize reactive maintenance. Its success in this area will be reflected by the percentage of time that is allocated to proactive, instead of reactive, projects.

5.2 Recommendations for Managerial Utilization of the Optimization Model

Recommendations for Present Usage

It is hoped that this thesis provides insight into the challenges and potential solutions for performing batch build manufacturing in a low-volume automotive production environment. The goal of the developed model is to provide decision support on key batch build strategy questions such as, *how large should batch sizes be given other constraints* and *how sensitive is the production system to a given input or variable?* This math-based tool is intended for use by any team member at General Motors involved in operations planning for the Halo program.

Although there are definite benefits derived from using math-based tools, providing managers and engineers with analytical tools does not guarantee that they will be used. The major issue with implementing this model as a decision support tool will be the confidence that the user places in the results and the ability to utilize those results for meaningful decision making. As Nguyen (2001) points out, the “trust loop” or confidence that the operator has in the output of the model is an important factor in model adoption success. Furthermore, Nguyen’s research shows that some of the major implementation issues “did not have to do with technical modeling obstacles, but rather with the cultural and organizational issues surrounding math analysis usage.” It is important that users of the model understand both its capabilities and its limitations in order to achieve successful adoption.

Future Usage of the Model

The author of this thesis strongly believes in the use of mathematical models to aid in strategic and tactical decision making. He will be returning to General Motors in a full-time capacity to help launch and ramp-up the SSR into full-scale production. He plans to continue to expand and further develop the model and strategy presented in this thesis. Continued involvement with the Halo program will help him to create a more robust model and actually test the results of the model against reality, as GM introduces additional Halo vehicles into its production system.

5.3 Further Considerations for Low Volume Niche Vehicle Manufacturing

Niche Demand

A further question to consider for the Halo program is, *if demand greatly outstrips supply, how does GM respond to such a situation?* Utterback (1994) describes a problem with niche product demand, i.e., it can very often grow to become mainstream demand and even takeover the previously dominant product²⁶. If that happens, GM must then decide if it is willing to increase supply to partially, or fully, meet the burgeoning market demand. If GM decides to meet a significantly higher demand, the Halo manufacturing strategy must be reevaluated to accommodate higher volumes. In such a scenario, GM must consider moving a Halo vehicle into a traditional high-volume production facility.

The flip-side of the issue is if the product demand does not sufficiently meet the produced supply. Although they are not low-volume products, the Volkswagen Beetle and the Chrysler PT Cruiser are niche vehicles that have experienced a measurable drop-off in demand as the “buzz” factor around their respective market segments have worn off. It is possible that Chrysler hedged its bets by constraining capacity, which then caused an immediate shortfall with the demand generated by the buzz. Volkswagen’s shortfall was that it rode a major wave of buzz with the new Beetle, but it appears that the company did not think beyond the buzz and have alternative versions of the product ready for the market soon enough.²⁷ The lesson

²⁶ Utterback, *Mastering the Dynamics of Innovation*, 1994.

²⁷ Peter M. DeLorenzo, *Chasing Rainbows In The New Marketing World*, 2002.

to be learned for GM is that although the Halo vehicles will be highly unique models produced in low-volumes only, the hype created by them may wear off faster than anticipated, as consumers hunger for the “next new thing”. It is thus advisable for GM to prepare a number of derivative Halo vehicles, perhaps along the lines of an annual or bi-annual model change. It is possible that GM and its partner-supplier can update the exterior design details and bodywork, while keeping the basic “hard points” of the vehicle intact, and minimizing cost incurred.²⁸ The manufacturing strategy designed for the Halo program should be able to accommodate these derivate vehicles with a minimum of difficulty.

Alternative Manufacturing Options

Although the Halo program plans to convert the existing low-volume LCC facility over to handling multiple niche products, an alternative strategy may warrant investigation. Since a requirement for the program is that all Halo vehicles are built off an existing product platform, it could make sense to build each Halo product in the in the high-volume plant of the product it most closely resembles. For example, the SSR is derived from a high-volume, BOF SUV platform and thus could potentially run down the same production line that makes the trio of sport utility vehicles based off that platform.

A benefit of this strategy is that it does not require a separate plant to handle the low-volume product and can potentially absorb the overhead costs associated with the Halo vehicle into the main high-volume facility. The major detriment to building niche vehicles in a volume plant is opportunity cost. Many of GM volume plants are currently building high-volume vehicles at maximum capacity. Therefore, every niche vehicle built at the volume plant is one less high-volume car or truck that can be sold. The cost of equipping and readying a dedicated low-volume niche vehicle plant such as the LCC may be justified compared to the lost revenues and profits created by displacing high volume products with niche vehicles in the volume plant. Furthermore, the added complexity of introducing a derivative product that could be quite dissimilar from the mainstream products can lead, to lower overall quality and increased downtime, among other disadvantages for the volume plant.

²⁸ Hard points are the fixed locations of the product that are used for locating other components on the body or frame and for locating the vehicle on the conveyor or skid in the factory.

5.4 Conclusions

This thesis was the culmination of tactical and strategic investigation into General Motors manufacturing policy for the newly developed Halo vehicle program. The challenge for the program is to devise a manufacturing strategy for multiple Halo vehicles, derived from different platforms and architectures, all manufactured on the same fixed line in the low-volume production facility. The Halo initiative is the first time General Motors is developing a single-plant manufacturing strategy dedicated to multiple low-volume vehicles. Therefore, this program represents a learning experience for the managers and engineers at GM and its partner-supplier who are involved with the Halo program, as well as for the operations and engineering staff at the Lansing Craft Center. This program is unique in that it requires fundamentally new ways of looking at automotive manufacturing, and hence of doing business.

Although the Halo batch build manufacturing system provides the required flexibility and minimizes capital investment, this thesis research found that batch build manufacturing across vehicle architectures is extremely rare in the automotive industry and thus engenders many unknowns. It is expected that further details will have to be gathered regarding, for example, actual changeover processes and methods, feasible equipment and tooling design, more concrete hardware and changeover costs, and line-side space requirements for tooling, before the General Motors batch build strategy team is certain that the Lansing Craft Center can effectively manufacture unique vehicles using a batch build production system.

It is hoped that this thesis will serve as a starting point for further examination of the batch build manufacturing strategy. Undoubtedly, many of the concepts and findings described herein will undergo iterations as GM, its partner-supplier and the LCC acquire more experience with the Halo production system. Furthermore, it is hoped that the knowledge contained in this thesis will provide strategic insights and recommendations to future Halo teams, enabling each new vehicle to readily integrate with the developed batch build strategy.

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Appendix A – Interview Process Guide

Halo Manufacturing Strategy Development

Introduction:

Due to the unique low-volume requirements of the Halo manufacturing system combined with outsourced nature of the Halo vehicle development, a number of unique issues and challenges must be addressed in order to successfully break with traditional General Motors' manufacturing methodology. To profitably manufacture the low volume Halo vehicles, GM needs to devise a manufacturing plan that will permit highly differentiated products, based off varied product platforms and vehicle architectures, to all be manufactured on the same fixed line. But a number of key questions arise that require original answers to be formulated.

The purpose of this interview is to better understand the issues and questions surrounding the manufacturing strategy for the Halo program, and discuss potential solutions to these areas of concern. I am hoping that you can provide insight into the equipment, material, labor and logistical, and supply chain issues of low-volume production for the Halo vehicles.

I will probe you to gather qualitative data regarding what you consider to be key uncertainties and concerns. The data obtained from this discussion will be used to help formulate a thesis plan and structure a batch build optimization model.

General exploratory questions:

- What is your title and organizational unit? Please describe your level of involvement and / or familiarity with the Halo program?
- What is your opinion of the overall Halo Program strategy?
- In what ways are the Halo program attempting to do things differently from a typical GM program? What makes you enthusiastic about this new way of doing business? Alternatively, what are your concerns about this new way of doing business?
- What is your vision of the Halo manufacturing system? What do you envision as the biggest obstacles to achieving such a vision?
- What are the major issues you see regarding the changeover process between vehicle models?
- How does the low-volume Halo manufacturing strategy differ from GM's traditional high-volume manufacturing strategy?
- What actions can be taken to mitigate the effect of an outsourced development partner producing a vehicle for manufacture on a GM line in a GM factory?

- What are your thoughts on the frequency of changeover between models? How frequently should we build each model? How can we determine optimal ideal batch sizes?
- How should the order-to-delivery (OTD) requirements be established for the unique Halo vehicles? How can the Halo manufacturing strategy best meet the OTD requirements?
- When and what should be broadcast for general assembly?
- How can we forecast paint colors to be built in any one batch? What should the straggler strategy be for unit that missed the original batch? How should we reintroduce stragglers into the system?
- What type of new operator skills and training are required to support a batch build system?
- How can we handle material in general assembly that is not consumed due to incomplete batches?
- Are there any organizational, cultural or personnel issues that you see arising as a result of implanting the Halo Program in general? How about for batch build manufacturing more specifically?

Appendix B – Introduction to Linear Programming Optimization Methods

What is Linear Programming?

(For rigorous definitions and theory, which are beyond the scope of this thesis, the interested reader is referred to the many linear programming textbooks in print, a few of which are listed in the references section.)

To understand linear programming, it is first beneficial to describe the nature of mathematical optimization. In basic *unconstrained optimization*, the idea is to find the greatest or smallest value of some *objective function* (Figure B1). For optimization to be required, there must be more than one solution available. In Figure B1, any point on the function $F(x)$ is a solution, and because the single variable is real-valued, there are an infinite number of solutions. Some type of optimization process is then required in order to choose the very *best* solution from among those available. What is meant by *best* depends on the problem at hand: it could mean the solution that provides the most profit, or that consumes the least of some limited resource, i.e. production capacity or raw material.

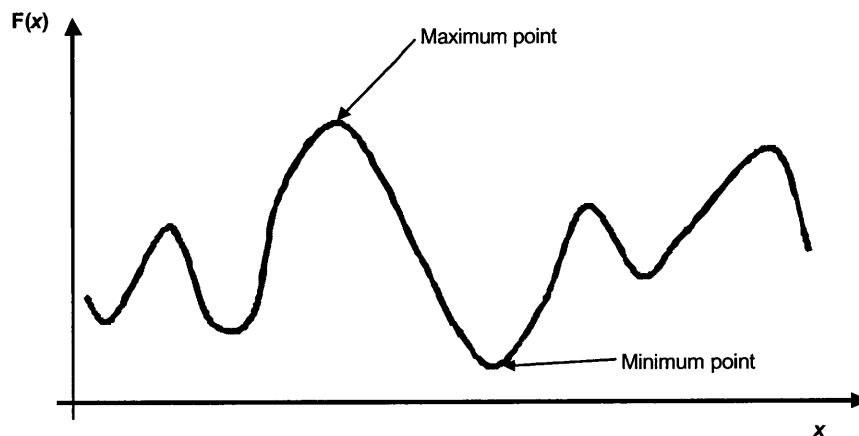


Figure B-1. Simple Unconstrained Optimization

Linear programming (LP) is the mostly commonly applied form of *constrained optimization*. Constrained optimization is significantly more difficult to solve than unconstrained optimization because it is still necessary to find the best point of the function but now it is also necessary to satisfy various constraints while doing so. For example, it must be guaranteed that the optimum point does not have a value above or below a pre-specified limit when substituted into a given constraint function. The constraints usually relate to limited resources. The simple mathematical method of using derivatives to find global maxima and minima of a function won't work anymore. With a constrained optimization, the best solution (the *optimum point*) may not occur at the top of a peak or at the bottom of a valley. The best solution might occur half way up a peak when a constraint prohibits movement farther up.

The main elements of any constrained optimization problem are:

1. **Decision Variables.** The values of the decision variables are not known when the problem is initiated. The decision variables usually represent parameters that can be adjusted or controlled, for example the rate at which to manufacture items. The goal of the optimization is to find values of the variables that provide the *best* value of the objective function.
2. **Objective Function.** This is a mathematical expression that combines the variables to express the goal. For example, it may represent profit, cost or equipment utilization. The optimization requires either a maximization or minimization of the objective function.
3. **Constraints.** These are mathematical expressions that combine the variables to express limits on the possible solutions. For example, they may express the idea that the number of machines available to perform a particular task is limited, or that only a certain amount of instrument panels are available per day.
4. **Variable Bounds.** Only rarely are the variables in an optimization problem permitted to take on any value from $-\infty$ to $+\infty$. Instead, the variables usually have bounds that constrain their feasible values. For example, zero and 500 might bound the weekly production rate of vehicles on a specific assembly line.

In *linear programming (LP)*, all of the mathematical expressions for the objective function and the constraints are linear. Linear programming is the most widely used of the mathematical techniques for constrained optimization. The terminology “programming” in this sense does not imply computer programming; it is a dated word for “planning”. Hence “linear programming” can be thought of as “planning using linear models”

A linear program is a problem that can be expressed in the following *standard form*:

$$\begin{array}{ll} \text{Minimize:} & cx \\ \text{Subject to:} & Ax = b \quad \text{and} \quad x \geq 0 \end{array}$$

Where x is the vector of variables to be solved for, A is a matrix of known coefficients, and c and b are vectors of known coefficients. The expression cx is called the objective function, and the vector equations $Ax = b$ are called the constraints. The matrix A is generally not square, hence one can't solve an LP by just inverting A . Usually A has more columns than rows, and $Ax = b$ is therefore quite likely to be under-determined, leaving great latitude in the choice of x with which to minimize cx .

Although all linear programs can be put into the standard form shown above, in practice it may not be necessary to do so. For example, although the standard form requires all variables to be non-negative, most robust LP software allows general bounds $LB \leq x \leq UB$, where LB and UB are vectors of known lower and upper bounds. Individual elements of these bounds vectors can even be $-\infty$ and/or $+\infty$. This allows a variable to be without an explicit upper or lower bound, although of course the constraints in the A -matrix will need to put implied limits on the variable or else the problem may have no finite solution. Also, LP software can handle

maximization problems just as easily as minimization since in effect, the vector c is just multiplied by -1 . Basic software packages such as the Solver application imbedded in Microsoft Excel or MathWorks' MATLAB can handle linear programs with a reasonable number of decision variables. For large-scale optimizations, a commercial program with increased computational power is required.

The importance of linear programming derives in part from its many applications (described below) and in part from the existence of good general-purpose techniques for finding optimal solutions. These techniques take as input only an LP in the above standard form, and determine a solution without reference to any information concerning the LP's origins or special structure. They are fast and reliable over a substantial range of problem sizes and applications.

Two families of solution techniques are in wide use today. Both visit a progressively improving series of trial solutions, until a solution is reached that satisfies the conditions for an optimum. The *simplex method*, introduced by Dantzig about 50 years ago, visits "basic" solutions computed by fixing enough of the variables at their bounds to reduce the constraints $Ax = b$ to a square system, which can be solved for unique values of the remaining variables. Basic solutions represent extreme boundary points of the feasible region defined by $Ax = b$, $x \geq 0$, and the simplex method can be viewed as moving from one such point to another along the edges of the boundary. *Barrier* or *interior-point methods*, by contrast, visit points within the interior of the feasible region. These methods derive from techniques for nonlinear programming that were developed and popularized in the 1960s by Fiacco and McCormick, but their application to linear programming dates back only to Karmarkar's innovative analysis in 1984. Research on improved methods continues to this day.

The related problem of *integer programming* that is dealt with in the optimization model for this thesis requires some or all of the variables to take integer (whole number) values. *Integer programs* (IP) often have the advantage of being more realistic than LPs, but the disadvantage is that they are significantly more difficult to solve. The most widely used general-purpose techniques for solving IP problems use the solutions to a series of LPs to manage the search for integer solutions and to prove optimality.

Linear programming is by far the most widely used method of constrained optimization. The largest optimization problems in the world are LPs having millions of variables and hundreds of thousands of constraints. With recent advances in both solution algorithms and computer power, these large problems can be solved in practical amounts of time.

Linear and integer programming have proved valuable for modeling many and diverse types of problems in planning, routing, scheduling, assignment, and design. Industries that make use of LP and its extensions include transportation, energy, telecommunications, and manufacturing of many kinds. A sampling of applications can be found in many LP textbooks, in books on LP modeling systems, and among the numerous application cases optimization journals.

Appendix C – Equipment and Tooling Changeover Analysis

This appendix details the work I performed as part of the tactical contribution to the batch build strategy team. I assumed worst-case scenario for tooling changeovers with the body-on-frame SSR converting over to a unibody Halo2 and vice versa.

My goal was to develop a changeover strategy for tooling monuments at all stations in the Body, Paint and General Assembly factories. The method followed was to: (1) Review the planned LCC layouts for SSR and Halo2, (2) Tour the Body, Paint and GA factories to develop detailed understanding of current process flow and equipment, and (3) Work with SSR and Halo2 Engineering Leads and Manufacturing Engineers to define tooling monuments and key parameters associated with the Halo changeover process. For each of the stations in Body, Paint and General Assembly factories, I was tasked with understanding, defining and documenting:

- Order in process flow and location on the line
- Manufacturing process performed
- Components installed and material presentation plans
- Tooling and equipment required
- Changeover process performed
- Changeover time (approx.)
- Manpower allocation
- Issues and feedback for product development teams

The major tooling and equipment monuments investigated for each of the sub-factories were:

Body Shop

Underbody bases
Skid hardware
Framer / Gates
Manual weld guns
Robotic weld guns
Subassembly / component load assists

Paint Factory

Skids / transfer hardware
Dip & spray processes
Drying ovens
Flash oven
Robotic spray processes

General Assembly Factory

Door removal assist
Roof stack load assist
Instrument panel load assist
Glass tooling nest
Battery load assist
Seat load assist
Door load assist
Frame load assist
Spare tire load assist (truck vs. car)
Chassis carriers
Axle load assists
Engine load assist
Fuel tank loader (car)
Marriage scissor-lift
5-lug / 6-lug nut runners
Fluid fill nozzles / hardware
Wheel alignment equipment
Headlight aim equipment
Dynamic Vehicle Testing equipment
Single Spindle Tools

BODY SHOP

LINE	STATION #	PROCESS	PARTS INSTALLED	TOOLING / EQUIPMENT	CHANGEOVER PROCESS	CHANGEOVER TIME (approx)	COMMENTS
Underbody	B01	Manual spot weld & toy-tab underbody subs	Motor compartment, Front floor, Rear compartment	Underbody base fixture, hanging weld guns, sealer pump	Manually roll out/in underbody bases on casters. Swap weld guns.	10 min	UNDERBODY BASES: worst case, fixturing stored near line and manually rolled out/in on casters. If idle underbody fixturing is too close to in-use hardware, may move to a storage area. Best case, common underbody tooling with pin details. WELD GUNS: utilize separate quick-change guns heads for SSR & Halo2. Air & water will quick disconnect, power may need manual connection. Halo2 will carry the cost of implementing weld gun tool changers. SUBASSEMBLIES: No subassemblies done in LCC - floor, rear comp and motor comp arrive in LCC as complete assemblies from the partner-supplier. ISSUE: Common sealer must be used across all Halo products or additional hardware/changeover is required.
Underbody	Transfer B010-to-B020	Transfer station-to-station	N/A	Overhead manual air-powered chain hoist with unique end effector.	Quick disconnects for air line & end effector.	10 min	Disconnect / reconnect air line & changeout end effector for each product. This assumes worst case, however Halo2 & SSR may be able to maintain a common end effector.
Underbody	B020	Seal, load and weld rockers, cross-sill and rear bulkhead panels. Perform additional manual underbody spot welds	SSR: LH / RH rocker subs, cross-sill assembly, RR bulkhead assembly Halo2: LH / RH rocker subs, tunnel reinforcement	Underbody base fixture, hanging weld guns (common for rockers, unique for tunnel reinforcement), sealer pump	Manually roll out/in underbody bases on casters. Swap weld guns.	10 min	UNDERBODY BASES: fixturing stored near line and manually rolled out/in on casters. If idle underbody fixturing is too close to in-use hardware, may move to a storage area. WELD GUNS: utilize separate quick-change guns heads for SSR & Halo2. Air & water will quick disconnect, power may need manual connection. Halo2 will carry the cost of implementing weld gun tool changers. SUBASSEMBLIES: No subassemblies done in LCC - floor, rear comp and motor comp arrive in LCC as complete assemblies from the partner-supplier. ISSUE: Common sealer must be used across all Halo products or additional hardware/changeover is required.
Underbody	Transfer B020-to-B030	Transfer station-to-station	N/A	Overhead manual air-powered chain hoist with unique end effector.	Quick disconnects for air line & end effector.	10 min	Disconnect / reconnect air line & changeout end effector for each product. This assumes worst case, however Halo2 & SSR may be able to maintain a common end effector.
Underbody	B030	Manual re-spot	none	Underbody base fixture, hanging weld guns	roll out/in underbody bases, changeout weld guns	10 min	Underbody base fixturing stored near line. How to roll base fixturing out/in? How to move hanging weld guns out/in? TBD after tooling vendor is selected.

Underbody	Transfer B030-to-B040	Transfer station-to-station	N/A	Overhead manual air-powered chain hoist with unique end effector.	Quick disconnects for air line & end effector.	10 min	Disconnect / reconnect air line & changeout end effector for each product. This assumes worst case, however Halo2 & SSR may be able to maintain a common end effector.
Underbody	B040	Manual stud installation / welding	studs	Underbody base fixture, stud installation tools	Manually roll out/in underbody bases on casters. Swap stud install tools.	10 min	Some studs have dimensional / locational importance, therefore must be done in LCC after underbody is complete and cannot come in on sub-assemblies. Halo2 uses the same three stud types as the SSR. Need future Halo products to stay within the same three stud types used on the SSR or additional tooling is required. The partner-supplier installs underside studs, GM installs topside studs.
Underbody	Transfer B040-to-Skid	Transfer station-to-skid	N/A	Overhead manual air-powered chain hoist with unique end effector.	Quick disconnects for air line & end effector.	10 min	Disconnect / reconnect air line & changeout end effector for each product. This assumes worst case, however Halo2 & SSR may be able to maintain a common end effector.
Main Line	Skid	Transport body through weld line (without precision location)	N/A	Skid hardware	Manual drop-away locating pins to change between models	10 min	Brand new skids will be designed to build in maximum flexibility based on current product definitions. Best case - common skid with no changeover required. Assumption that front hole locations are the same for SSR/Halo2. 78 skids used in system. ISSUE: Can same skid be retooled for Halos 3/4? Unknown if all products can run on single skid. ISSUE: Who will flip the tooling details? There is no job currently at this location.
Main Line	Cross Transfer	Accumulator buffer between A-side and B-side of weld line	N/A	N/A	N/A	N/A	Accumulator can hold 10 bodies as a buffer between underbody line and main weld line. Target is to have accumulator filled with bodies before beginning changeover to keep main line fed during changeover.
Main Line	H010	Transfer from cross x-fer to main weld line conveyor	N/A	Skid transfer equipment	N/A	N/A	Same transfer used for all skids/ all products
Main Line	H020	Idle (?)	N/A	N/A	N/A	N/A	N/A

Main Line	H030	Load, seal and toy-tab inner side subs, mate inner & outer header and attach to vehicle.	LH / RH inner sides, Front header, Front bulkhead brackets	Inner side manual load assist, sealer guns, manual header tool (at header subassembly station only), vice grips for toy-tapping	Quick change load assist end effector.	10 min	Inner / outer headers subassembly station is located next to main line. Utilize quick changeover end effectors based on product. ISSUE: Common sealer must be used across all Halo products or additional hardware/changeover is required.
Main Line	H040	Gate storage (inner gates)	N/A	Framer gate	Roll out/in gates per product	Included in Framer H050 change-over	TBD: Will the gate change be manual or use some level of automation? ISSUE: Need automation to move large gates out/in rapidly (~15 secs with automation) and allow nearly simultaneous changeover of gate and underbody tooling. However, automation currently not authorized in tooling plan.
Main Line	H050	Inner Framer	N/A	Gates & underbody fixture, manual spot welding guns	Roll out/in gates, change underbody fixturing, swap weld guns	10 min	Installing new framer on main line. Underbody tooling changeover mimics process on B-line. ISSUE: time, skill level needed to change over underbody hardware. Who is capable of doing the 'wrenching'? Is there sufficient technical staff to perform changeover? ISSUE: Common changeover issues with weld guns. Halo2 carry cost of implementing weld gun tool changers.
Main Line	H060	Gate storage (inner gates)	N/A	Framer gate	Roll out/in gates per product	Included in Framer H050 change-over	TBD: Will the gate change be manual or use some level of automation? ISSUE: Need automation to move large gates out/in rapidly (~15 secs with automation) and allow nearly simultaneous changeover of gate and underbody tooling. However, automation currently not authorized in tooling plan.
Main Line	H070	Manual MIG re-spot	N/A	Manual MIG welding guns, resistance weld guns	N/A	0 min	No MIG welding currently on SSR. MIG welding is used on the Halo2 tunnel cap (4 seams). Should be able to use existing MIG hardware for all products that require MIG welding. No changeover needed, same MIG hardware accommodates multiple products. No underbody bases needed for precision location.
Main Line	J010	Robotic re-spot	N/A	Robot-held weld guns	Changeout underbody bases, change software program, change weld guns	10 min	Differences between weld locations on products will drive need to change weld guns. Tool changers will allow robots to automatically changeout and set-up weld gun for each product. Weld gun tool changers will not be installed until Halo2 arrives in LCC.
Main Line	J020	Robotic re-spot	N/A	Robot-held weld guns	Changeout underbody bases, change software program, change weld guns	10 min	**This station will move to after the outer framer. Differences between weld locations on products will drive need to change weld guns. Tool changers will allow robots to automatically changeout and set-up weld gun for each product. Weld gun tool changers will not be installed until Halo2 arrives in LCC.

Main Line	J030	Manual re-spot	N/A	Hanging weld guns	Swap weld guns	10 min	Manual re-spot for locations robots cannot access. ISSUE: Common changeover issues with weld guns. Halo2 carry cost of implementing weld gun tool changers.
Main Line	L005	Load, seal and toy-tab outer side subs	LH / RH body quarters, outer fender assemblies	Outer side manual load assist, sealer guns, manual header tool, vice grips for toy-tabling	Quick-change load assist end effector.	10 min	Quick changeover end effectors based on product. ISSUE: Common sealer must be used across all Halo products or additional hardware/changeover is required.
Main Line	L010	Gate storage (future outer gates)	N/A	Framer gate	Manually roll out/in gates per product	Included in Framer L020 change-over	TBD: Will the gate change be manual or use some level of automation? ISSUE: Need automation to move large gates out/in rapidly (~15 secs with automation) and allow nearly simultaneous changeover of gate and underbody tooling. However, automation currently not authorized in tooling plan.
Main Line	L020	Outer Framer	N/A	Gates & underbody fixture, manual spot welding guns	Roll out/in gates, change underbody fixturing, swap weld guns (?)	10 min	Installing new framer on main line. ISSUE: time, skill level needed to change over underbody hardware. Need to analyze using PAAS vs. completely manual process. ISSUE: Who is capable of doing the 'wrenching'? Is there sufficient technical staff to perform changeover?
Main Line	L030	Gate storage (outer gates)	N/A	Framer gate	Roll out/in gates per product	Included in Framer L020 change-over	TBD: Will the gate change be manual or use some level of automation? ISSUE: Need automation to move large gates out/in rapidly (~15 secs with automation) and allow nearly simultaneous changeover of gate and underbody tooling. However, automation currently not authorized in tooling plan.
Main Line	L040	Manual re-spot	N/A	Hanging weld guns	Swap weld guns	10 min	Manual re-spot for locations robots cannot access. ISSUE: Common changeover issues with weld guns. Halo2 carry cost of implementing weld gun tool changers.
Main Line	L050	Protect for future load, seal and tab roof station	Roof (future Halo vehicles)	Perception station if funding is allotted, underbody bases	Manually roll out/in underbody bases on casters.	10 min	Protect for future fixed-roof Halo vehicles. Perceptron robotic vision system (for dimensional verification) is carried on robotic heads and does not require changeover. Underbody base fixturing stored near line and manually rolled out/in on casters. If idle underbody fixturing is too close to in-use hardware, may move to a storage area.
Main Line	Cross Transfer	Buffer between on main weld line	N/A	N/A	N/A	N/A	Cross transfer can hold 6 bodies as a buffer

Main Line	S010	Transfer from cross x-fer to main weld line conveyor	N/A	Skid transfer equipment	N/A	N/A	Same transfer used for all skids/ all products
Main Line	S020A	Load roof panels (SSR) / tonneau (Halo2) to slave fixturing	Front roof panel, rear roof panel	Roof panel / tonneau load assist	Quick-change load assist end effector.	10 min	Custom designed to hold SSR roof panels though paint. **TBD - how to handle Halo2 tonneau panels. May be painted outside and delivered to GA.
Main Line	S020	Load roof / tonneau slave fixture to body. Fuel filler door bolt on	Roof slave with panels & fuel filler door	Manual load assist for slave fixture, nut runner for fuel filler door	Quick-change load assist end effector.	10 min	Common install location for fuel filler door on all platforms
Main Line	S030A	Hinge pierce	N/A	Product-specific hinge pierce tooling, product-specific locating hardware	Change hinge pierce locating hardware	10 min	Hinge hole locations (spread and size) need to remain constant across products. Halo2 hole locations are currently the same as SSR. ISSUE: If future products are derived from a new architecture, may need to change over hinge pierce tooling.
Main Line	S030	Install fender bracket, door	LH / RH fender bracket, LH / RH doors	Manual load assist for doors, nut runners	TBD	TBD	Evaluating differences between SSR & Halo2. May need to change over end effectors.
Main Line	S040	Install front fenders	LH / RH front fender	Manual load assist for doors, nut runners	Quick-change load assist end effector.	10 min	Changeout fender end effector for each product.
Main Line	S050A	OFF-LINE SUBASSEMBLY: Install hood hinge to hood & pierce holes	Hood, tailgate (SSR) / tonneau (Halo2)	Manual load assist for hood and tailgate/tonneau	Quick-change load assist end effector.	10 min	Changeout hood end effector for each product. Changeout tailgate/tonneau end effector for each product.
Main Line	S050	Install hood, tailgate/tonneau	N/A	Manual load assist for hood and tailgate/tonneau	Quick-change load assist end effector.	10 min	Changeout hood end effector for each product. Changeout tailgate/tonneau end effector for each product.
Main Line	S060	Install braces	Fender and quarter pencil braces (SSR specific)	Nut runners	N/A	N/A	N/A

Main Line	S070	Panel Fitting	N/A	N/A	N/A	N/A	N/A
Main Line	S080	Metal Finish	N/A	Metal finishing tools	N/A	N/A	N/A
Main Line	S090	Quality Gate	N/A	N/A	N/A	N/A	N/A
Main Line	S100	Hold doors open for paint	N/A	Model - specific jigs to hold doors open	N/A	N/A	N/A
Main Line	AGV Transfer	Transfer to AGVs to paint	N/A	N/A	N/A	N/A	N/A

ISSUES:

- 1) **B-ZONE WELD GUNS:** Will require specific guns for each model based on product definition. Finalizing SSR guns now. Once Halo2 definition is available, will make determination on level of commonality. **ISSUE:** Quick-change guns must be mounted on the floor and could be in the way of other tools.
- 2) Production belt runs at a fixed transfer speed so changeover bubble is additive - lose 5 minutes per station. May need to stop transfer to do changeover. Stop-and-go roller stations on main line do not have this problem.
- 3) Is 4-job accumulator between body and paint enough to buffer factories? Potential to lose 5 jobs per changeover due to body shop changeover.
- 4) Potential opportunity to change over skid details after body is unloaded from AGV and skid returns to storage. Could implement sensors to check for correct details before sheet metal can be loaded.
- 5) Official published plant charter is 30 min changeover
- 6) Biggest challenge is making skids and carriers capable of carrying multiple products.

Appendix D – Halo Production Optimization Model

Batch Size Optimization Model Using Simplex Linear Programming

A sample of the optimization model with quarterly time frames is shown in Figure D-1 below:

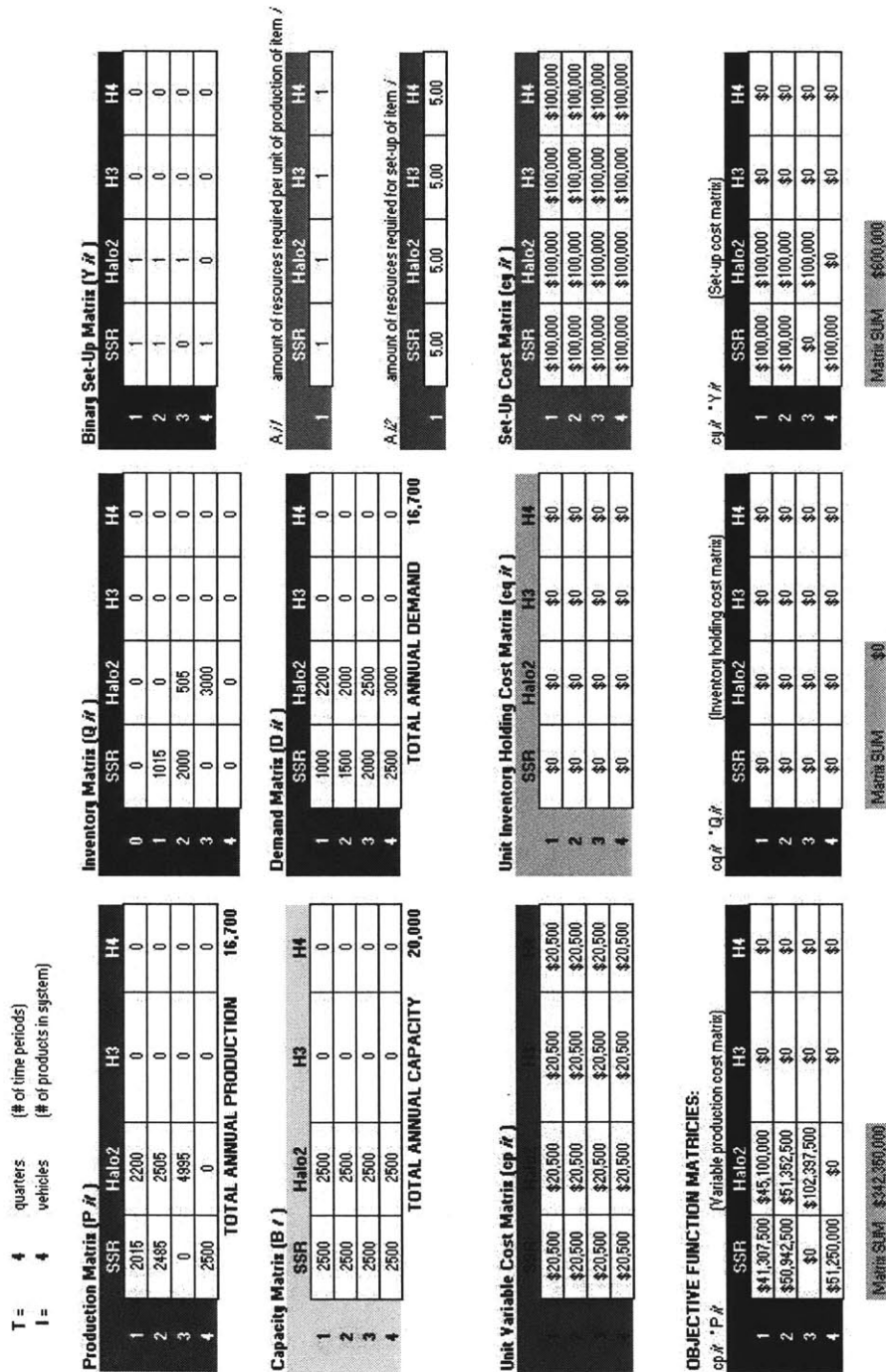


Figure D-1. Example Optimization Model with Four Time Periods

Appendix E – Sample Model Outputs

Production Matrix (Pit)				
week	SSR	Halo2	H3	H4
1	220	200	200	200
2	220	200	200	200
3	220	200	200	200
4	220	200	200	200
5	220	200	200	200
6	220	200	200	200
7	220	200	200	200
8	220	200	200	200
9	220	200	200	200
10	220	200	200	200
11	0	400	225	200
12	450	0	175	200
13	0	400	225	200
14	450	0	175	200
15	0	400	225	200
16	450	0	175	200
17	0	400	225	200
18	250	0	375	200
19	0	400	0	400
20	400	0	400	0
21	0	400	0	400
22	400	0	400	0
23	0	400	0	400
24	400	0	400	0
25	0	400	0	400
26	400	0	400	0
27	0	400	0	400
28	400	0	400	0
29	0	400	0	400
30	400	0	400	0
31	0	400	0	400
32	400	0	400	0
33	0	400	0	400
34	400	0	400	0
35	0	400	0	400
36	400	0	400	0
37	0	400	0	400
38	400	0	400	0
39	0	400	0	400
40	400	0	400	0
41	0	400	0	400
42	400	0	400	0
43	0	400	0	400
44	400	0	400	0
45	0	400	0	400
46	400	0	400	0
47	0	400	0	400
48	400	0	400	0
49	0	400	0	400
50	200	0	200	0
TOTAL ANNUAL PRODUCTION				40,000

Figure E-1. Sample Model Output for Reduced Inventory Holding Cost