Lean Automation Strategies for High Volume, High Complexity, Manufacturing Systems

by

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B.S., University of Illinois, Urbana-Champaign, 2008

Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

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Abstract

This thesis and the associated project explore lean automation strategies for high volume, high complexity manufacturing systems. In particular, we study how to reduce the footprint and cost of an automotive sealing line, while maintaining current levels of production, maintainability and safety.

The key challenge researched in this thesis concerns how to reduce space requirements and cost of a highly automated facility without sacrificing system maintainability, safety or throughput. For this study, any solution must utilize currently available technology.

The thesis will review the basic research, concept development, layout development and solution refinement activities that lead to a final concept and recommendation. The key findings for this study include three strategies that led to a lower cost footprint that consumed less space. These strategies are:

- Intelligent reduction of conveyance systems
- Increased system flexibility
- Increased automation density

Additionally the study highlights how these strategies complement each other when addressing cost and space reduction challenges. In this particular study the three strategies yielded space savings of approximately 33% and capital cost savings of about 10%.

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Also, several other members of the GM team and its suppliers truly helped me understand sealing processes and the implications of the concepts outlined in this thesis. Thank you Prateek Mishra, Dean Doherty, Dave Kracko, Peter Swiecicki, Sharon Schutte, Greg Welch and Dean Waineo for all your help in my research for this project.

Also, my advisors, David Hardt and Thomas Roemer provided valuable advice and guidance throughout the internship and in helping me develop a strong thesis. David and Thomas, thank you for your help.

Last but not least, I have to thank my wife, Samantha for her support throughout the internship. Samantha told me to pursue an internship that I found exciting, regardless of location. She stuck to her word and supported me when I matched with an internship at GM, even though it meant we would spend six months apart. As a result I had the opportunity to explore an exciting industry and resurgent company in GM during my LGO experience.

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Chapter 1

Introduction

General Motors, more commonly referred to as GM, is one of the world's largest automotive companies. The company employs over 212,000 employees in 396 facilities on six continents. Its brands include Chevrolet, Buick, GMC, Cadillac, Baojun, Holden, Isuzu, Jiefang, Opel, Vauxhall and Wuling.[2]

In North American vehicle manufacturing facilities, GM has continued to invest in new automation solutions that improve safety, cost, quality and throughput. The increasing complexity of vehicle designs has driven the need for new production solutions in many areas of an automotive manufacturing plant. In the paint shop, improved corrosion performance requirements push the capabilities of today's modern vehicle assembly sites. This project focuses on "paint shop sealing", a process which provides one of multiple layers of corrosion protection to modern vehicles.

1.1 Purpose of project

This project has the objective of reducing cost and footprint of a paint shop sealing line. More stringent requirements covering corrosion, noise, and cabin comfort have caused an increase in the amount of sealing content in today's automobiles. Sealing lines have grown substantially in order to accommodate these requirements. Space comes at a premium in a paint shop, and as a result there is a strong desire to reduce the space required by future sealing installations.

1.2 Problem statement

The key question for this project is *How might General Motors reduce the footprint of future greenfield paint shop sealing lines?*

The solutions to this problem statement must meet important constraints, in particular they must:

- Use existing technology and materials
- Only require changes to the sealing line

This means that we exclude concepts requiring significant R&D work, changes in product design or new practices for processes occurring before and after the sealing line.

At the outset of this study, we set four objectives for the project. Success would mean that the final solution and recommendation meets all four of the following criteria:

- Reduce sealer line footprint by at least 25%
- Reduce capital costs by 10-20%
- Maintain or reduce operating costs
- Meet the throughput and maintainability requirements of the facility

1.3 Approach

The project proceeds in four phases: Problem Definition, Research & Analysis, Solution Development and Refinement. This approach allows for consideration of a broad number of potential solutions and concepts at the outset. Then, as we collect additional data, we narrow down and regroup concepts into viable solutions. The final phases refine the highest potential ideas into a solution which GM can reference for future sealing line applications.

1.3.1 Problem definition

During the problem definition phase we focus primarily on two areas. First, we focus on developing a detailed understanding of the processes involved in sealing and overall paint shop. Then second, we clearly articulate the scope, context and problem statement for the project.

The first part of this phase looks at the design motivation and evolution of automotive paint shops over time. Documenting paint shop design philosophy aids the understanding of why paint shops and sealing lines have their current arrangements. After building an appropriate understanding of sealing lines, this phase moves to documenting and reviewing vehicle body requirements in terms of corrosion, leak and noise performance.

Building on this detailed understanding of the paint shop and product requirements, we move on to structure the key problem statement for this project - *How might General Motors reduce the footprint of future greenfield paint shop sealing line installations?* This problem statement, guided by the aforementioned project constraints, help focus efforts and expectations for subsequent investigations.

1.3.2 Research and analysis

Following completion of the problem definition phase, we move on to researching potential solutions. This phase begins with developing a collectively exhaustive list of categories for investigation, and prioritizing those concepts based on ease of implementation and potential impact.

Activities during this phase include interviews and idea generation sessions with experts. It also entails bench-marking activities across multiple industries as well as within the automotive industry. After describing a list of potential concepts, we conduct rough feasibility assessments and narrow down the list of potential concepts.

1.3.3 Solution development

The solution development phase prioritizes potential layouts that utilize one or more of the compression concepts from the research and analysis phase. We combine an initial list of high-potential discrete concepts into three high potential layouts and solutions for the problem under investigation.

Each solution receives an evaluation that gauges impact (with respect to the project's objectives) and feasibility. Key analyses included developing hypothetical layouts, process flows, and high level assessments of the strategic implications of each solution.

1.3.4 Refinement

After selecting a primary solution from the prior phase, the activities in the Refinement phase focus on building a robust level of detail around the primary solution.
We complete three additional analyses in this phase:

- Cell designs
- Engineering layouts
- Process simulation

These deliverables form a package that clearly identifies the capabilities, risks, and remaining investigations associated with the recommended solution. This enables us to make informed decisions on when to apply concepts from the final recommendation to new or existing facilities.

Chapter 2

Manufacturing Engineering at GM

This section discusses the role of Manufacturing Engineering - Vehicle Systems, the organization hosting this project, within GM. It is intended to provide the reader with an understanding of the context of this project. The following sections will touch on the overall objective of the Manufacturing Engineering organization and the host team - *Vehicle Systems - Global Center, Paint Materials and Facilities* plays within the larger organization. Subsequent sections will provide the reader with baseline understanding of automotive paint shops, their associated processes and additional detail on sealing processes and history.

2.1 Manufacturing Engineering - Vehicle Systems

Manufacturing Engineering - Vehicle Systems encompasses the teams responsible for designing, installing, and upgrading paint shops and general assembly lines. This scope includes all associated equipment and infrastructure, as well as process engineering. Additionally, the organization hosts experts responsible for supporting manufacturability reviews for new product introduction.

While manufacturing locations have their own dedicated support teams on site, Vehicle Systems also hosts numerous subject matter experts that support troubleshooting as needed. The organization, overall, operates in a hybrid model, whereby some responsibilities are truly global roles, while others focus primarily on North American sites.

Vehicle Systems - Global Center, Paint Materials and Facilities, the team hosting this project, is one of the organizations with global scope. This group develops paint shop processes, investigates and develops new technologies and provides troubleshooting support to manufacturing sites. Working with this team on a day to day basis afforded us the opportunity to review concepts and ideas utilized around the world both within and outside GM.

2.2 Overview of paint and sealing process

Paint shop processes apply coatings and treatments that serve as a vehicle body's primary line of defense against multiple types of wear and tear. Sealing processes prevent water, dust, noise and fumes from entering a vehicle cabin through body seams. Paint processes prevent body panel corrosion and damage to underlying structural and sheet metal.

The paint shop in vehicle manufacturing is typically the second step within an assembly site. Vehicle assembly starts in the body shop, where pre-stamped body panels and structural materials are welded together. After the body shop, come paint shop processes. The paint shop then sends fully painted and sealed vehicle bodies to general assembly, where operators complete the final assembly of a vehicle.

Figure 2-1 shows the overall flow of processes within a vehicle assembly site. It also shows the three main phases within the paint shop: Pretreat and ELPO, Sealing, and Paint.

The pre-treat and"so-called" elpo process first cleans and prepares a vehicle body for an anti-corrosive paint layer. After cleaning, subsequent tanks apply a conversion coating which improves the ability of anti-corrosive paint, often referred to as the elpo layer, to adhere to the vehicle body. The elpo phase uses an electro-deposition process to evenly coat the entire vehicle body with an anti-corrosive layer of paint. This type of process helps the coating adhere to all surfaces, even in areas where fluid flow is restricted. After the pre-treat and elpo process, the vehicle proceeds through an oven. This hardens and bonds the elpo layer

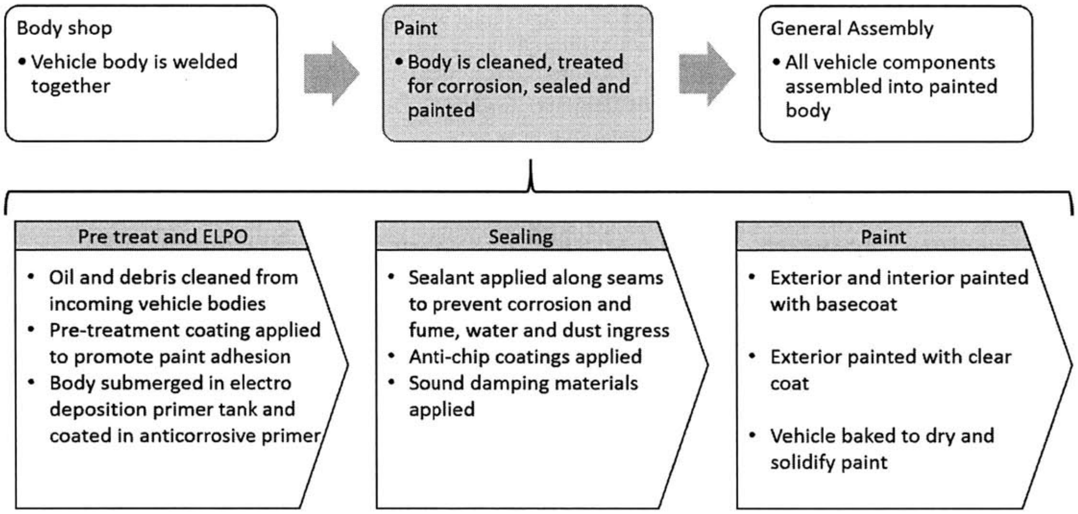


Figure 2-1: Paint shop process overview

to the substrate (the vehicle body in this case).

The sealing process begins with several manual processes including removing any dirt and dust off of the elpo layer, installing production aids and inserting plugs for drain holes in the vehicle body. After this step, the vehicle moves through a seam sealing process, sound damping application, underbody sealing and application of anti-chip coatings. This process also includes several manual activities to inspect and touch up sealer application. Sealing finishes with an oven that bakes the sealer.

Following sealing comes the actual painting step. Most automotive facilities have moved to entirely automated paint processes due to the high repeatability and reliability of modern robotics. During the paint process, robotic applicators apply a basecoat primer, colored base coat and clear coat to the vehicle. Bake cycles of varying duration are mixed into the process based on process type and paint technology. After final baking, the vehicle receives a thorough inspection. It then enters general assembly.

2.2.1 Sealing process detail

The sealing line itself can vary from facility to facility, but for the purposes of this study we focused on five types of sealing activities.

1. Seam sealing: A process by which sealant is applied to seams formed by overlapping body panels. Vehicles may have seams located on the underbody, interior, engine compartment or trunk of a vehicle. OEMs complete the process through the use of automation or manual operations.
2. Underbody coating: This process is more commonly used to protect vehicles with high amounts of cold rolled steel (versus galvanized steels which feature much greater corrosion resistance). During the underbody coating process, a hand-held or automated sprayer applies a PVC based sealer across the entire underbody of a vehicle.
3. Liquid Applied Sound damping: This is an automated application of liquid sound damping material. The material used varies between automotive OEMs, but all serve to reduce noise by preventing the vibration of body panels.
4. Hem seal: A hem is any location where the body shop has folded one piece of metal over another. Common locations for vehicle hems include doors, deck lids and hoods. Hem sealing often uses material similar to that used in seam sealing. However, hem sealing requires greater accuracy and narrower application beads due to its high visibility locations and often tight clearances with other pieces of the vehicle body.
5. Anti-chip: This process sprays a thin layer of PVC material to protect the ELPO paint layer from chipping. The application of anti-chip material typically occurs on locations subject to significant abrasion from road debris such as stones or gravel.

2.2.2 Sealing history at GM

Up until the 1980s GM had applied seam sealers almost entirely through manual processes. However, in the 80s OEMs began introducing early versions of hydraulic robots. These versions of sealing robots faced several issues. In particular, hydraulic automation displayed very low reliability and limited accuracy [1].

In the 1990s, automotive robots began adopting digital servo motors. This technology shift dramatically improved the accuracy and reliability of paint and sealing robotics. Facilities producing truck bodies were the first to use seam sealing robots. Truck beds featured long, relatively straight seams. This made them more suitable for early adoption of seam sealing automation. Additionally, at this point in time, GM began utilizing lighter weight sealing materials in order to reduce vehicle weight.

By the 2000s, sealing automation began to deliver significantly improved accuracy, precision and reliability. During this time period, GM car plants in North America began to adopt sealer robots as they offered enhanced quality at lower cost than manual processes. Additionally, the new generation of robotics and automation enabled the adoption of liquid applied sound damper (LASD). Previously, operators had to manually apply dozens of damping pads to each vehicle. Each vehicle usually had unique pads and pad arrangements. This process created significant complexity within the paint shop. LASD replaced most of these pads with a liquid damping material that could be applied very quickly while enabling an improvement in process and product flexibility.

Also during the 2000s, GM began using significantly greater amounts of sealing content across all vehicle types. As a result, older paint shops began running out of available floor space for new sealing operations.

Modern sealing lines in North America and high labor cost regions can now feature eight or more fully automated cells that complete seam sealing, LASD application, hem sealing and anti-chip processes. However, human operators still show a superior ability to spot defects, work sealer into seams and remove excess material buildup along areas that often interfere with later assembly steps.

Chapter 3

Literature review

The literature review will highlight some of the key research relevant to this study. In particular it will cover the role of automation in a Lean manufacturing environment, relevant approaches to production systems and optimizing facility layouts.

3.1 Lean Manufacturing

In this section we will discuss the central tenets of Lean manufacturing and its objectives. Additionally, this project focuses on the usage of automation. So we will review some of the implications of Lean on highly automated processes.

3.1.1 Overview of Lean

Lean manufacturing is a practice that considers any consumption of resources for any reason other than adding value for the end customer as wasteful [9]. In particular, Lean targets the elimination of "7 wastes" including defects, overproduction, transportation, waiting, inventory, motion and processing.

Lean manufacturing is often combined with a larger manufacturing system (at GM this is called their Global Manufacturing System or GMS). In a larger manufacturing system, Lean is integrated with effective use of existing technology, policies and human resources. Lean, when integrated into a larger system can have significant impact on efficiency. The former GM facility, NUMMI, implemented of a version of Toyota's Lean production system and delivered a 40% productivity improvement [10].

3.1.2 Automation and Lean

Despite the success of Lean production practices overall, there exists debate on the role of automation within a Lean environment. Arguments against automation can stem from increased complexity and downtime. Implemented incorrectly, automation may instead drive up inventory levels as well. Krafcik, in his research, noted observations of highly automated facilities with large repair areas and teams of men working alongside robots to ensure proper completion of tasks. Compounding this issue, operators expected to solely monitor processes fail to maintain adequate visual attention for more than about thirty minutes [4].

Some of the prejudice against automation and Lean working well together may come from obeservations of Lean practitioners. In 1990 Womack *et al.* published observations of very lean and productive Japanese automotive factories utilizing little automation and ineffecient Western factories using a great deal of automation [16]. However, perhaps one of the best known Japanese practitioners of Lean, Toyota, includes a pillar in its production system called *jidouka*. This principle advocates for the use of "automation with a human touch". Since 1990, Toyota has become one of the greatest users of advanced manufacturing technology in the world [11].

Hedlind and Jackson completed a set of case studies to understand why some Lean practitioners could successfully implement automation, while others saw their efficiency suffer. In their research they found successful Lean automation users typically practiced four strategies [8].

1. High degree of in-house knowledge and limited use of third-party integrators
2. A focus on how the technology supported the solution, rather than a solution supporting the technology

3. First building familiarity with automated mistake proofing, then moving to robotics
4. Human-centric solutions

Hedlind and Jackson's research highlighted Lean practitioners that found ways to incorporate automation and improve productivity. So, while it appears that many firms have struggled with effectively combining automation with Lean, thoughtful and strategic implementation of automation in a Lean environment can work and yield significant benefits.

3.2 Machine and system production modeling

In this section we discuss how we characterize a production system and the potential sources of variability in overall production. This discussion is relevant to a key step in evaluating the capability of any proposed sealing line solution and whether or not it will meet the constraints set forth in this investigation. This discussion will focus on the types of moving production lines common in the automotive industry.

A manufacturing system such as a sealer line, is a series of automated and manual operations completed in sequence to deliver a final product. In the case of this study, it is a sealed automobile. Each operation is completed to transform raw material (sealer, plugs, a vehicle body) into the final product.

In the manual stages, a series of operators work alongside a moving conveyance line carrying the vehicle body. Each stage is designed to take an equal amount of time, called the *Takt time.* An operator within a stage is assigned a set of tasks to complete within the *Takt time.* The actual time to complete the task is referred to as the *cycle time.*

Sources of variation and downtime in manual stages can come from several sources. These include quality issues (such as damaging an uncured seal bead), break time, or an operator just struggling to complete a task within a given *Takt time.*

Automated processes follow much of the same approach, with work split across multiple steps designed to be completed within a given *Takt time.* However, automation is often subject to additional sources of variation. Automation is subject to breakdowns and often cannot handle input variation and in-station correction tasks as well as a human operator.

For automotive production processes in general, variation in production can come from multiple sources. These include areas such as material shortages, breakdowns, reworks and non-standard production needs [7].

In order to combat variability and downtime, several strategies have been explored. These may involve introducing some redundancy in a system or through the use of buffers, which mute the impact of downtime and variation. Or, a process could leverage a new line design, such as a parallel line [5].

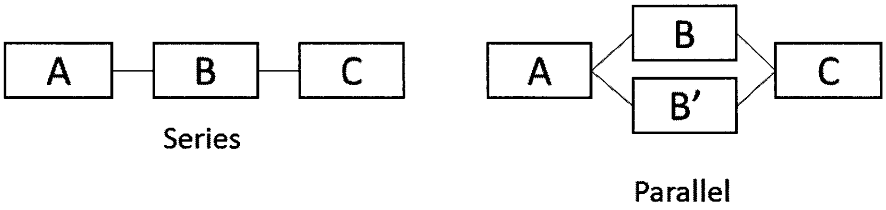


Figure 3-1: Series vs. Parallel manufacturing lines

The advantage of a parallel line stems from the fact that down time from one parallel process may not impact the total line rate. For example, in Figure 3-1, if B' were to go down, the line may still run, albeit at a reduced rate.

When assessing the likely throughput of a system, numerous variables should be considered. This includes mean time between failures, mean time to repair, mean cycles between failures and stand-alone throughput. The interactions of all these parameters between stages along with how one models variability in a system all play a role in designing a production system that meets shop goals at an appropriate cost.

3.3 Optimizing factory layouts

The implementation of Lean manufacturing systems by their very nature, eliminate excess inventory and reduces non-value-add activities. This on its own opens up opportunities for reducing factory production space. For example, during a Lean implementation conducted for a medical device manufacturer [19], it was found that the team could reduce inventory on hand by locating material at point of use. This eliminated almost half the storage space for large items in the facility.

Additionally, factory layouts are considered a key influence on facility efficiency and operating costs. As such, the topic has been studied across industries for many decades. Initial research showed advantages of using cellular layouts versus traditional functional layouts. But, cellular layouts can suffer from low utilization and high capital costs [15].

Approaches to optimizing layouts can take an agnostic view to the the cellular vs. functional debate but will typically fall into two categories - Algorithmic and Procedural [18].

Algorithmic approaches attempt to translate design constraints and system objectives into an objective function. This function often attempts to minimize an objective such as line length or cost. However, this approach may not capture critical qualitative criteria.

Procedural approaches may incorporate quantitative assessments, but largely rely on the qualitative inputs of experts to identify the optimal layout [12]. As a result, the selected design is sometimes subject to personal biases. This study uses a procedural approach to designing a new factory layout.

An example of an algorithmic approach appears in a study by Peters and Yang [13]. In their study of a semiconductor fab layout they utilized a space-filling curve and network flow model to optimize the layout of a material handling system. Their network flow formulation sought to minimize the tradeoffs between the distance saved by building a shortcut, with the capital cost incurred with using that shortcut.

A Lean implementation study completed by AlEisa, Chen, Peterson and Yang [3], [6], [14], [19] utilized a more procedural approach and one that looked at individual processes in more detail. Their project focused on how to reduce footprint at a facility by optimizing manpower, visual management, cycle time and inventory. In conjunction with these efforts, their research highlighted four steps to optimize a facility layout.

1. Remove non-production areas from the production floor
2. Decentralize inventory to point of use
3. Consolidating equipment
4. Adjusting configurations of equipment

We will later discuss how items 3 and 4 apply to the sealing line investigated for this study.

Yang attempted to reduce the trade-offs between algorithmic and procedural approaches through use of a fuzzy multi-attribute decision making model [17]. This approach attempts to assign numerical relative values to the inputs of an expert and then use those values to algorithmically solve for an optimal layout solution. However, the implementation still relied on several pre-developed layout designs for evaluation. The approach did not create layouts from scratch.

Chapter 4

Research & Analysis

This section will dive into the first two steps of our investigation: current state analysis and concept development. The next chapter will discuss how we turn a combination of concepts into a layout and refine it into a full recommendation. The objective of this approach is to start out by defining a broad set of alternatives. Then we will eliminate and prioritize concepts as we collect additional detail and complete evaluations. This approach maximizes the breadth of alternatives at the outset, while maintaining an efficient design process.

4.1 Current state analysis

Prior to developing proposals for an improved sealer line layout, we complete a series of investigations into the current state of the sealer line. This requires investigation of a baseline facility. Additionally, this phase includes valuable cultural observations that could influence the viability of any proposal.

4.1.1 Facility and products

The facility serving as the project baseline manufactures sedans for GM. It is a good example of one of GM's highest volume facilities, capable of running three shifts six days per week. The assembly plant includes three major manufacturing phases - *Body shop, Paint shop* and *General assembly*

The paint shop includes three different stages as well - *Pretreatment and ELPO, Sealer, Paint.*

The facility recently underwent major renovations and received an entirely new paint shop. This new paint shop leverages all of GM's latest technology and layout strategies. As such, the project begins with a baseline demonstrating the most current approaches available.

4.1.2 Layout of the facility under investigation

This section will review the baseline layout for the sealing line under investigation. The next section will review the characteristics of individual processes. This layout will serve as the basis for illustrating the impact of certain strategies used throughout this study. The layout also utilizes common acronyms for the sealing processes - *UBS* refers to "Underbody Sealing", *ISS* refers to "Interior Seam Sealing", *LASD* refers to "Liquid Applied Sound Damper", and *HEM* refers to "Hem Sealing". In the layout below it's important to observe the following characteristics.

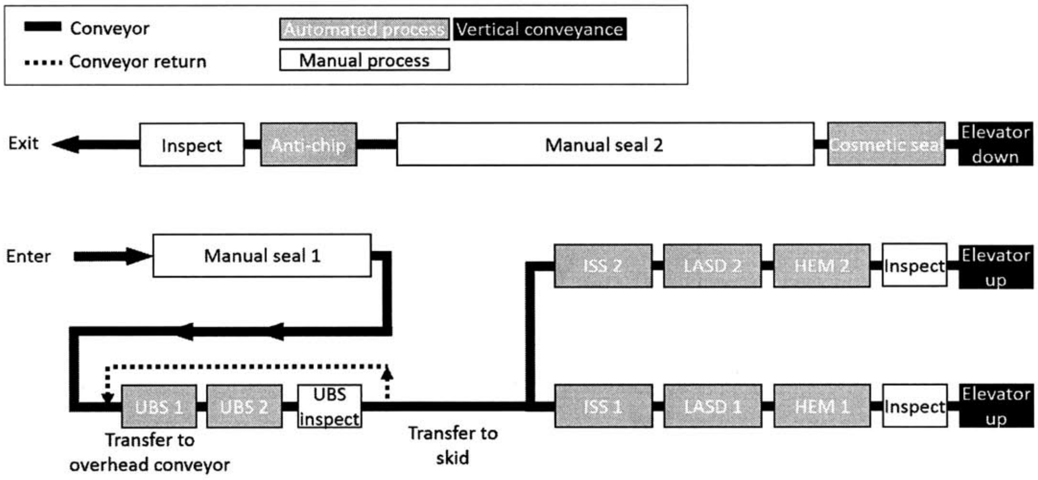


Figure 4-1: Baseline layout for sealing line under investigation

1. The production line has aisle access on both sides
2. Aisles are kept clear through the use of elevators which transfer vehicles over the aisle

3. The line is "U" shaped, limiting the maximum distance between stations and facilitating easier communication and visual management
4. Grouping of manual and automated zones to eliminate isolated islands for operators

Additionally, we should note the variety and type of conveyance used to facilitate this process. Any manual processes will use continuous conveyance, automated processes utilize stop station conveyors. All processing steps require the vehicle to enter a cell with its front facing forward. In order to meet this constraint, the site must use turntables and horizontal transfer types of conveyors. Finally, we can observe in the above figure, accessing the underbody of the vehicle requires the use of overhead carriers which elevate the vehicle. For the UBS steps, the conveyance must elevate the vehicle enough such that the automation can reach all the required underbody seams.

Each automation cell typically features an arrangement where two robots operate on rails on either side of the vehicle. These robots have six axes of movement and long arms optimized for reaching in and out of vehicles. In addition to the four applicator robots, a cell can utilize multiple door opening and visual inspection robots as well.

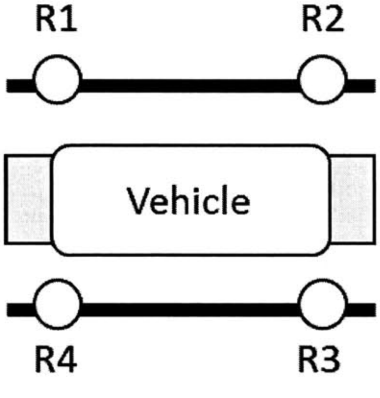


Figure 4-2: Automated sealing cell layout

Manual processes will utilize raised decks alongside a moving conveyor line. The decks also have special lighting to improve visibility and hold all necessary tooling, consumables and production aids alongside the line.

4.1.3 Processes

This facility contains 10 processing steps in order to completely seal the vehicle. These processes include those described in Chapter 2's overview of the paint and sealing process, but also include additional opportunities for manual intervention and rework processes.

Step	Process Name	Process type
1	Manual seal 1	Manual
2	Underbody seal	Automated
3	Interior seam seal	Automated
4	LASD	Automated
5	Hem seal	Automated
6	Cosmetic/Roof Ditch	Automated
7	Manual seal 2	Manual
8	Anti-chip	Automated
9	Final inspect	Manual
10	Seal oven	Automated

Table 4.1: Sealing line process overview

The process design represents a highly intentional approach to utilizing the best capabilities of both humans and automation. Automated systems handle tasks involving taxing movements, difficult seam tracking or high application speeds. Human operators focus on non-repeatable steps such as brushing away excess material, pushing sealant deeper into seams and inspecting high risk areas on the vehicle body.

Process capability is another important aspect of documenting the baseline process. We analyze and document each process step along several performance parameters to help us understand the throughput performance of the shop. The list of parameters includes:

- **Station speed**: The gross rate, in jobs per hour at which the station operates
- **Stand alone availability**: The percentage of working time during which a station is available for work; this value views a station as an independent entity and does not account for station blocking, starvation and planned downtime
- **Stand alone throughput**: The net rate, in jobs per hour at which a station operates after accounting for unscheduled downtime

- **Mean time to repair**: The mean time to repair a station after a failure or fault occurs

We enter the data into our simulation model in order to complete a simulation and determine the theoretical rate at which the baseline will produce vehicles. We use a simulated throughput baseline for two reasons. First, the line under investigation was not yet completed. Second, running a simulation for both the baseline and proposed solution allows us to have a fair comparison between the two approaches. We've created the figure below as a disguised representation of the baseline process. Data is purely artificial and is simply intended to support our discussion. In our example the the sealing line is intended to meet a rate of at least 28 jobs per hour (JPH). Each process's stand alone throughput is provided in jobs per hour and highlight buffer sizes in terms of small, medium and large.

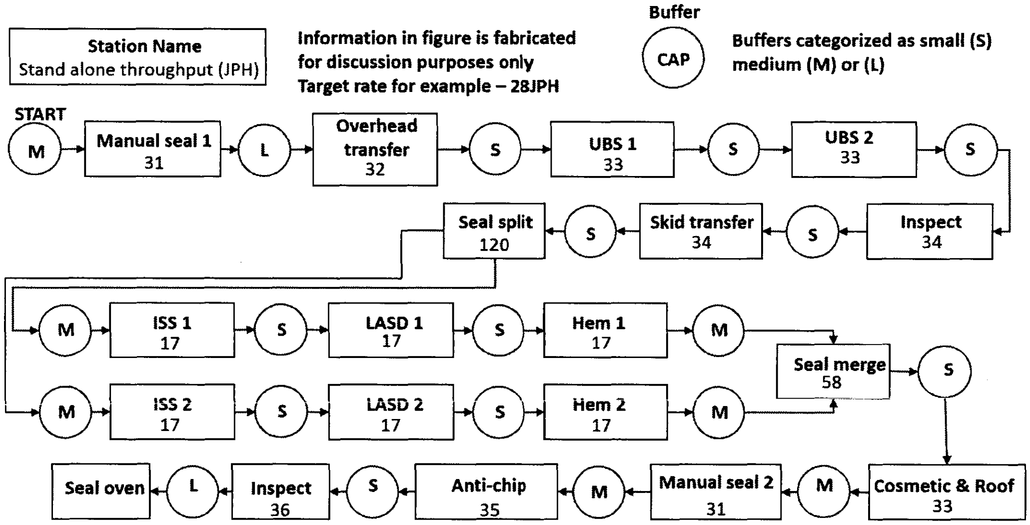


Figure 4-3: Disguised representation of model used to determine throughput of baseline sealing line layout

In the figure above, we observe some important traits of the baseline system. Many of the line's processes are intentionally designed to run faster than the target shop rate. This is driven by uncertainty in the amount of sealing content required by future vehicles, and uncertainty in the true throughput capability of the line. It also provides additional capacity and time for repairs.

For those processes which involve sealer application, we collect data on sealer application rates. This analysis serves to document the maximum amount of sealer content (in terms of length or area) that the process can handle while still meeting the overall throughput requirements of the paint shop.

- **Tip speed**: The speed, in millimeters per second at which a manual or automated applicator applies sealer material
- **Path efficiency**: The percentage of processing time spent actually depositing sealer material on a seam or surface, due to complex paths and part geometries the applicator spends a significant amount of the processing time on positioning and orientation movements
- **Index time**: The time required to move a vehicle from one station to the next and position it within a sealing station
- **Part locating time**: The time required to locate specific parts on a vehicle prior to commencing sealing processes
- **Entry and exit time**: The time required for an operator or robot to enter a vehicle through a window, trunk or engine compartment prior to applying sealant (this is accounted for separately from path efficiency)

Path efficiency, index time, part locating time and entry and exit time all reduce the amount of available processing time for completing a sealing step. To determine the maximum viable sealing content (in terms of seam length) for a specific operator or robot on a process step we use the following formula.

Let

$$t_1 = Takt\ time$$

$$t_2 = Index\ time$$

$$t_3 = Part\ locating\ time$$

$$t_4 = Entry\ and\ exit\ time$$

Then

$$Max\ sealing\ content = \frac{(t_1 - t_2 - t_3 - t_4)(Path\ efficiency)}{Tip\ speed}$$

In addition to documenting each activity, this phase also includes understanding the materials and their engineered properties. The following table outlines the types of materials utilized for each process step.

Process name	Material type
Underbody seal	Standard sealer
Interior seam seal	Standard sealer
Hem seal	Standard sealer
LASD	Liquid sound damper
Roof Ditch	Exposed sealer
Cosmetic	Cosmetic sealer
Anti-chip	Air-spray sealer

Table 4.2: Materials used in sealing process

Understanding the materials used and their sequence plays an important role in later process design stages. Each material has requirements for ambient air curing as well as oven curing times. Additionally, sealer and LASD materials face compatibility issues.

4.1.4 Cultural observations

Understanding the prevailing culture at GM plays an important role in building a solution that the organization will readily accept. Within manufacturing engineering we identify a few key observations.

First, this project runs at a time when GM seeks to distance itself from the "Old GM" which had entered bankruptcy. This means that the project occurs at a time when the leadership team strongly encourages outside ideas and new thinking, a trend that bodes well for this initiative.

Second, the paint organization holds a long institutional memory. Most experts within the paint and sealing realm hold long tenures with GM. They've observed the success and failure of numerous past technologies. Paint and sealer materials can display surprising and often unwanted interactions with even the smallest variation in environment and input. The small differences that can create an out of control process are often at the forefront of people's minds. So, while the "New GM" pushes for new ideas, those involved with paint and sealing still display some wariness of new concepts.

Finally, the organization views safety and throughput as absolutely sacred tenets of GM's production philosophy. Any concept that negatively impacts either of these tenets faces a long and uphill battle for approval.

4.1.5 Observations within the automotive industry

The early bench-marking phases of the project also explore sealing practices across multiple major OEMs. These firms display a wide variety of approaches in their endeavors to fight corrosion through sealing. The following section examines variation in these practices across three areas.

- Material choices
- Manual processing
- Automated processing

Sealers are highly engineered materials, designed through close collaboration between automotive manufacturers and material suppliers. However, the materials in use often show remarkable similarity. Most OEMs use PVC based sealers and anti-chip materials. In some applications, OEMs require suppliers to mix in fillers to reduce the weight of sealants. For LASD applications, GM uses a water borne material. While this material causes some additional processing challenges, it offers environmental benefits over traditional solvent borne LASD materials used by other OEMs.

Manual seal processing activities appear to vary based more on region than based on OEM. All manufacturers reviewed in this study complete some form of post processing on a seal bead after initial application. Korean manufacturing sites will often brush 100% of the seal beads, removing excess material and pushing sealer into seams. Most other sites use a combination of brushing and skiving (using a rubber scraper to push material into seams and remove excess) in limited locations on the vehicle. These locations usually represent high corrosion risk, or high risk of interference with later assembly steps. Globally, the automation of seal application is highest in high wage regions, such as North America, and lowest in low wage regions and most emerging markets.

In terms of automated processing, we observe the greatest variation in conveyance decisions. While most sites demonstrate a common usage of robots on rails for application, decisions around conveyance vary quite dramatically. Most manufacturers utilize a combination of stop station and moving line conveyance for sealing processes. But, for underbody sealing, OEMs use a variety of means to access the underbody of the vehicle. Examples include:

- The use of large material handling robotics to lift and orient the entire vehicle
- Usage of electrified monorail systems - a type of stop-station overhead conveyor
- Rotisserie style conveyance systems, these solutions hold vehicles in carriers that can not only move forward and backward, but also rotate the vehicle along an axis running from front to back
- Installation of pits around a traditional line to enable underbody access

As part of the benchmarking phase, we also examine usage of sealers across additional industries. Two industries in particular come up as significant sealer consumers, although at an order of magnitude less than the automotive industry. These industries are consumer appliances and aerospace.

Consumer appliances such as microwaves, washers, dryers and refrigerators use latex based sealers for various applications. However, when compared to the automotive industry, the material application occurs along much less complex paths, at lower volumes and through more manual methods.

The aerospace industry offers some relevant examples of advanced sealer materials. Aerospace sealers have the benefit of curing at ambient temperature, strong adhesion and desirable elasticity properties. However, these types of materials prove cost prohibitive for automotive applications. Also, from an application process perspective, the aerospace industry uses entirely manual processes to apply sealer.

4.2 Concept development

This section will discuss the approaches for reducing the footprint and cost of the sealing line under investigation. It will also review criteria for selecting the best concepts for further investigation and potential implementation.

At the outset of our investigation, we break potential concepts into three overall categories. Then, within these categories examine groupings of tactics that fall within that category. An issue tree outlines the structure for our solution development.

The next three sections will review merits and weaknesses of approaches within each category along with some illustrative examples.

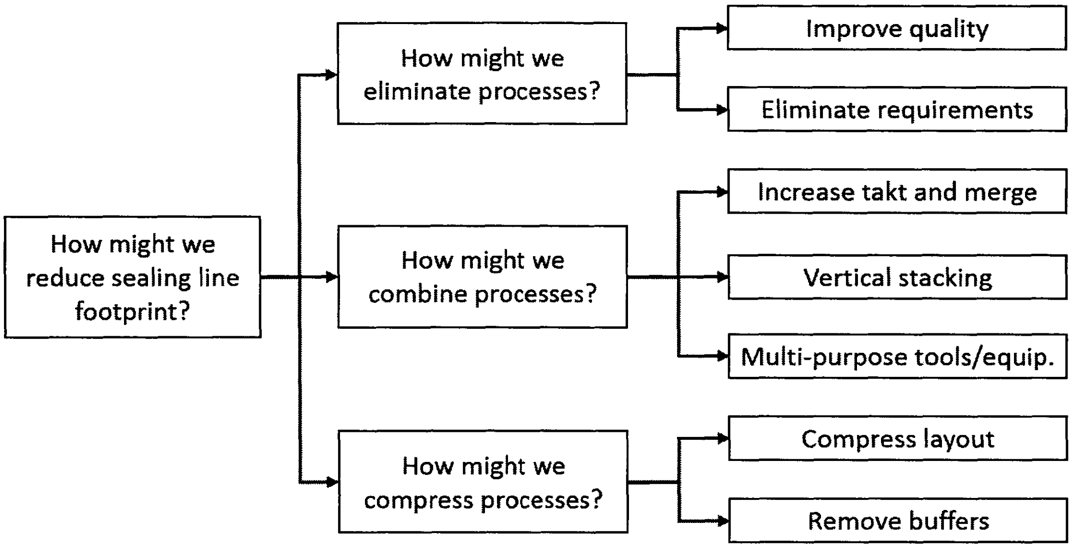


Figure 4-4: Issue tree utilized to group investigations

4.2.1 Eliminating processes

Eliminating processes offers an approach that has a simple implementation but often faces significant development challenges. For the purposes of this investigation, we examine two types of tactics for eliminating processes.

Improving quality is the first priority. Several of the activities in the steps described as *Manual Seal 1* and *Manual Seal 2* actually serve to check for skipped seams and excess material. Any enhancement to the application process that eliminates the need for these reworking steps likely reduces the total space and cost of the layout. Additionally, improvement in quality reduces the need for defect holding areas, and the additional conveyance required to insert or remove vehicles from the production line.

Reducing vehicle requirements is the second tactic for eliminating process steps. For instance, further investigation into seam leakage patterns could show that a vehicle requires less sealing content than originally thought. Additionally, sealing processes can be eliminated through the use of protective plastic moldings in place of sealer. However, given the limited duration of this investigation, we leave vehicle requirements untouched and focus solely on modifications to the manufacturing process.

4.2.2 Combining processes

Within the category of combining processes we include three tactics.

- Increasing takt time and merging processes
- Vertical stacking
- Multi-purpose tooling and equipment

Increasing takt time and merging processes entails identifying two processes to combine and increasing takt time to allow for both processes to occur at that station before indexing to the next step in the process. This approach requires the overall shop rate to drop, or moving from a serial line to a parallel arrangement.

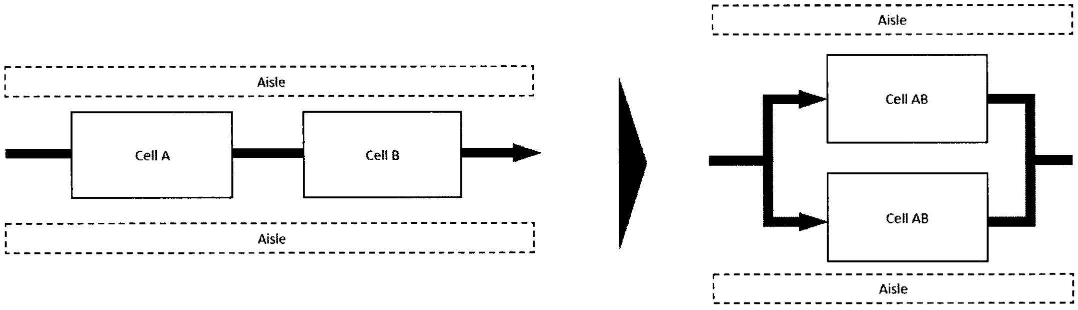


Figure 4-5: Impact of increasing takt time and merging processes

One of the main benefits to this approach is its failure mode. Rather that shutting down an entire line, a failure simply reduces the rate of the overall system. Properly designed, this approach can alleviate the need for higher redundancy levels present in traditional serial line arrangements. This reduces the size of an automation cell and ideally space as well.

However, upon further review, we find difficulties with achieving desirable space and cost reduction levels with this approach. Any space savings from a less complex cell, are somewhat offset by the additional conveyance needs of a parallel line. Also, aisle access to the middle station becomes more difficult.

The *Vertical stacking* tactic reduces space by combining processes that occur on separate sections of the vehicle. For instance, Liquid Applied Sound Damper (LASD) application can occur simultaneously with underbody sealing.

This approach derives space saving benefits by using empty space above a pre-existing cell to complete a task normally completed at floor level. It provides benefits by eliminating the space required by an entire cell and saves money by reducing conveyance requirements.

However, this type of arrangement can suffer from a few key issues.

- Stacking cells requires additional infrastructure investment
- Stacked arrangements can introduce maintainability challenges
- Building must have suitably high ceilings

The utilization of *Multi-purpose tooling and equipment* refers to completing multiple processes (such as LASD and Interior Seam Seal) within the same cell through the use of flexible tooling. It has the potential to significantly reduce the amount of automation required to complete a process.

If we refer to our approach to process documentation, we can see that non value added activities consume a portion of a process takt time. This includes steps such as vehicle indexing, part locating and entry/exit time. These steps consume a portion of a robot's potential processing time. If a robot can complete multiple processes, then a robot will spend a larger portion of its time applying sealers and less time on non-value added activities. This can be observed in the following example. We will simplify the comparison by only focusing on index and positioning time for two processes, A and B.

Demand = 60 jobs per hour (infers takt time of 60 seconds per cycle)
Index and positioning time = 20 seconds

Processing time A = 25 Seconds, 4 robots

Processing time B = 30 Seconds, 2 robots

Total time A = 25 + 20 = 45 seconds

Total time B = 30 + 20 = 50 seconds

When these processes occur independently, two automation cells are required. Cell A requires four robots and Cell B requires two robots.

However if we develop tooling capable of processes A and B, and split the workload of Cell B across the four robots already in A, then we eliminate the need for a second cell altogether.

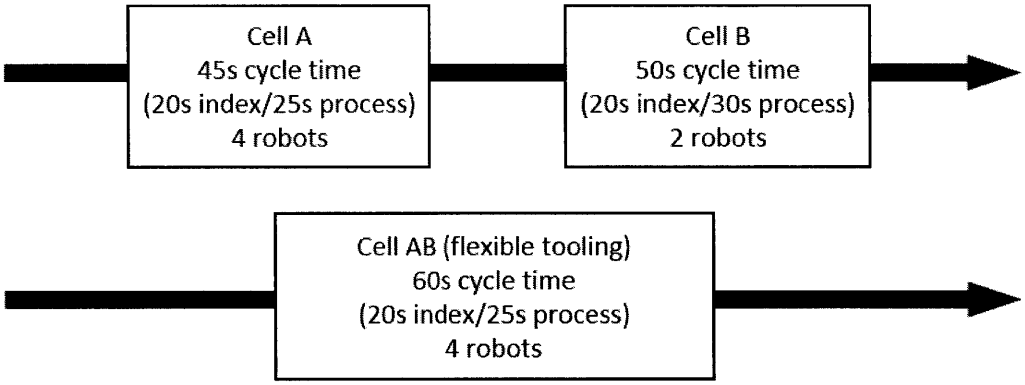


Figure 4-6: Illustration of space saving implications for multi-purpose cell

It's useful to think about this in terms of total processing time capacity in a cell. In our baseline, Cell A completes 100 seconds of processing (4 robots x 25 seconds per robot). Cell B completes 60 seconds of processing (2 robots x 30 seconds per robot). The combined cell completes 160 seconds of processing and this breaks down to 40 seconds of processing for each of the four robots. This allows for the completion of both tasks within one cycle.

The challenges in this approach come from identifying suitable combinations of processes that will allow for the elimination of equipment as in the example above. In our investigation we found several scenarios where combining processes would moderately exceed the line's initial takt time. In cases where a two lane parallel line existed, moving to a three - lane parallel line configuration could typically alleviate this issue while still reducing the amount of automation required. The addition of another applicator robot on an overhead section of the cell was another method for reducing the new cell's cycle time below the process takt time.

Different material requirements add another layer of complexity to this approach. As any multi-purpose tooling would require additional robot dress. This additional equipment can make it difficult for robotics to properly access confined areas of the vehicle.

4.2.3 Compressing processes

The final method explored for reducing the floor space and cost of the sealer line focused on compressing processes. We identified two methods for this approach. The first method involves shrinking the size of an automation cell, work area or conveyance system. The second method involves identifying and removing unnecessary buffers in the system.

Attempts to shrink work areas and automated cells typically yield several small opportunities with significant trade-offs. Existing designs intentionally include extra space that greatly enhances maintainability and accessibility along the manufacturing line. So, while removing some of these features saves floor space, they negatively impact some of the design objectives of the shop.

While shrinking existing cells and work areas may not offer great opportunities, new conveyance solutions provide another method to compress the overall layout. Most conveyance in the shop can only move the vehicle along a single axis. For instance, a stop-station conveyor goes forward and backward, a turntable simply spins the vehicle. Introducing new conveyors that can move along multiple axes enable significant reductions in the total conveyance required and allows for the use of novel cell designs.

The second approach, identifying and removing unnecessary buffers in the system can yield beneficial, low risk opportunities. This approach relies on a detailed analysis of system throughput and analyzing the utilization of each element in the line. Using the baseline system's throughput data, we can select buffers for removal and identify if any significant throughput penalties occurred.

4.2.4 Concept development and selection

In the preceding section we outlined the categories into which we group space and cost saving concepts for the sealing line. In this section we will discuss the development of those concepts and walk through the process by which we select the best concepts from within each category. This process follows approximately 3 steps:

- Idea generation
- Concept definition
- Concept prioritization

The *Idea generation* step includes several activities designed to build a broad range of concepts for consideration. During this phase we build out a list of potential space savings solutions through interviews, brainstorming sessions with stakeholders and some of the baseline analysis activities outlined in the previous sections. Idea generation is intended to be unconstrained at first, with low potential ideas culled through subsequent steps.

The *Concept Definition* phase includes documenting each of the ideas generated throughout the previous step. For this step we complete a one-page template that includes a description and rough diagram of the concept. Additionally, the template includes a list of key advantages and disadvantages of the concept.

The idea generation step generated a list of approximately twelve high potential concepts. Eight of those met the scope restraints defined at the outset of the project. We describe these eight concepts below.

Cell stacking - This approach stacks two complementary cells on top of each other. The cell holds the vehicle in place either on a fixture or through an unobtrusive conveyance method. Advantages for this approach include reducing floor space by one cell for each stacking arrangement and reducing overall vehicle processing time.

However, a key risk associated with this concept includes a potential costly and large support structure for the second level of automation. This structure would likely consume a portion of any space savings derived from this solution.

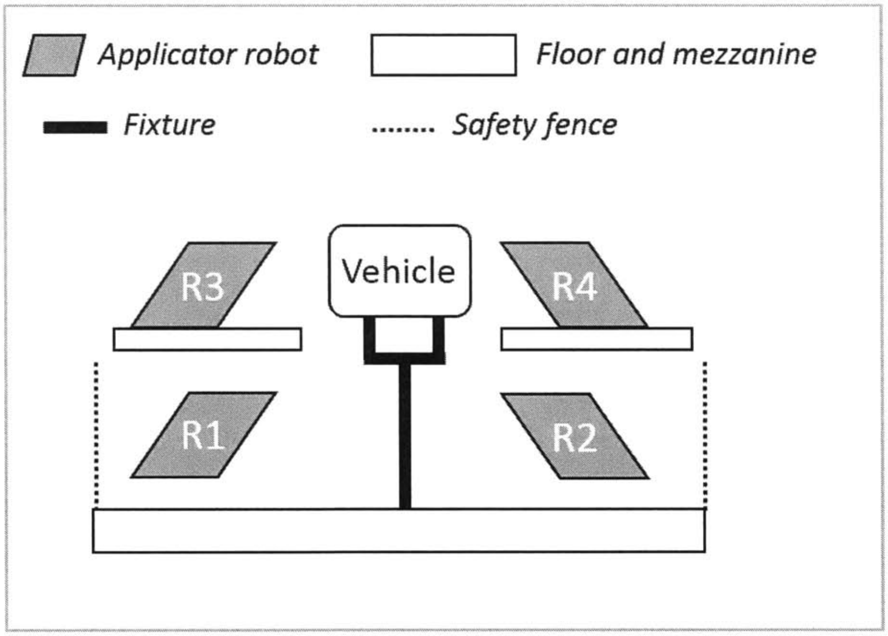


Figure 4-7: Concept diagram of stacked cell concept

Multi-axis shuttle and fixed multi-axis conveyor - These approaches utilize conveyance mechanisms that allow for vehicle positioning along multiple axes. The approach could either used a fixed conveyance system or a shuttle type system. Shuttle type systems can move along the line in addition to positioning the vehicle in multiple orientations.

A multi-axis conveyor can be used in multiple manners. In the most basic form, it may just replace an existing style of conveyance equipment. It could also be used to create the equivalent of a machining cell for a sealing operation. In this scenario, a single multi-axis

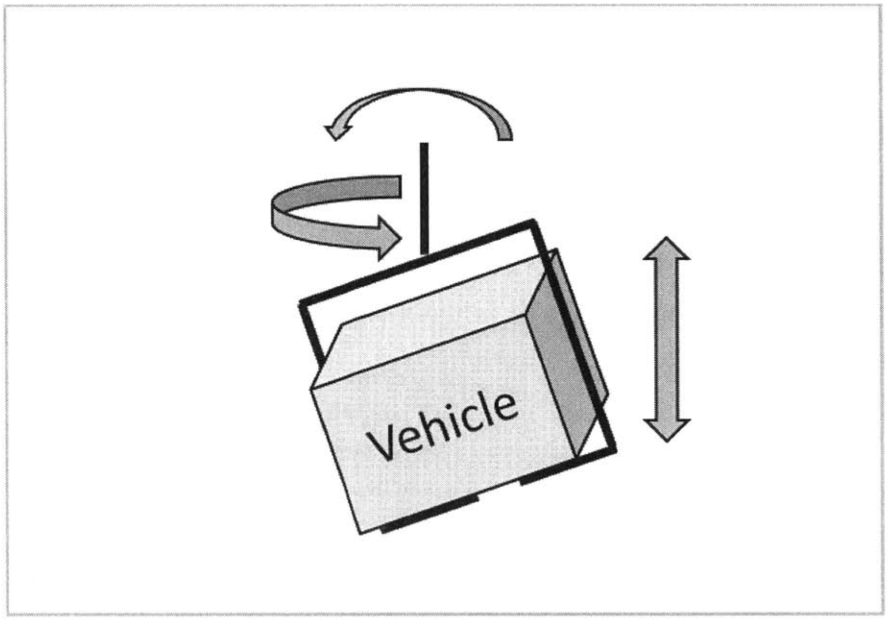


Figure 4-8: Diagram of 3-axis overhead shuttle

conveyor would hold on to a single vehicle, place it in a sealing cell, remove it and then place it in the next.

An advantage of these concepts is enabling new orientations of the vehicle. This could help robotics or people reach additional vehicle locations. Additionally, they can replace other types of conveyance in the system, such as turn tables and cross transfers. However, many of these solutions have high costs, introduce complex controls and require repair areas that take up space.

Multi-process and Parallel line - A parallel line approach on its own has the advantage of more "graceful failure" in that if one cell on a parallel line breaks down, the overall production rate only drops by a fraction. In our diagram below, one cell breaking down would only reduce overall line rate by 25%.

So, in instances where the parallel line model can be applied, it often has benefits. However, for our baseline sealing line model, UBS is the only in line process with enough content to justify two stations. However, if we introduce tooling capable of multiple processes (capable of delivering multiple stream geometries and/or materials) we can move to a parallel line model.

Using multi-process tooling has the advantage of increasing robot utilization as we discussed in the combining process section. This has the potential for reducing total number of robots and cells as well. But, this method introduces new and unproven tooling, and an increased likelihood of robots interfering with each other.

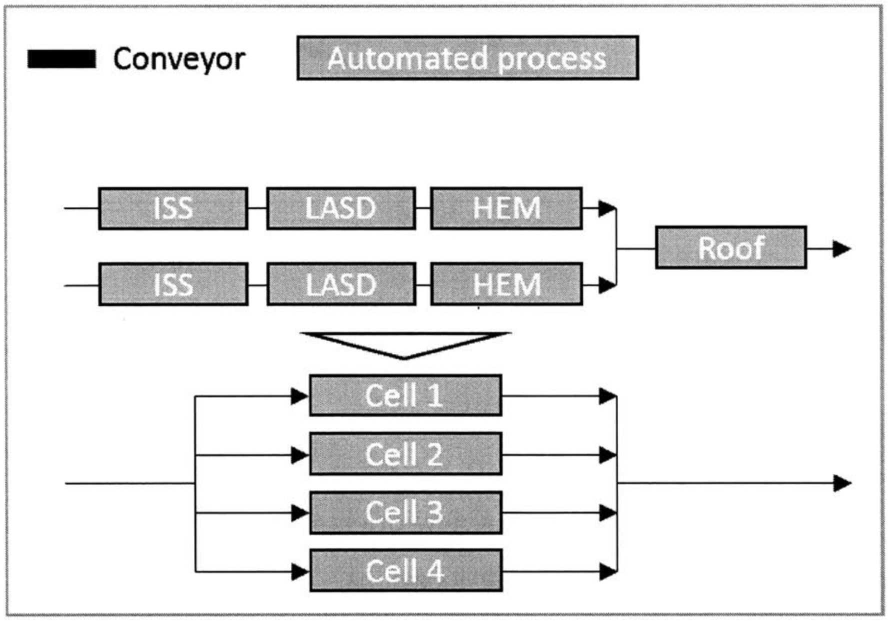


Figure 4-9: Concept diagram for parallel configuration of multi-process capable cells

Compressed cell - This approach shortens the linear length of a line by eliminating cross walks and buffers between process steps. It has the advantage of easy implementation and eliminating several feet of conveyance. However, with fewer buffers the line becomes more prone to disruption. Also, maintenance and operator access become more difficult.

UBS lift - The UBS lift concept utilizes lower cost floor mounted lifts that raise a vehicle to a higher conveyance line. This allows UBS robots to access the necessary surfaces. This approach uses common factory equipment and likely costs less than the current use of overhead carriers. Additionally, it eliminates the need for the overhead carrier return loop currently used today. This drives a space saving. However, this equipment has higher indexing times

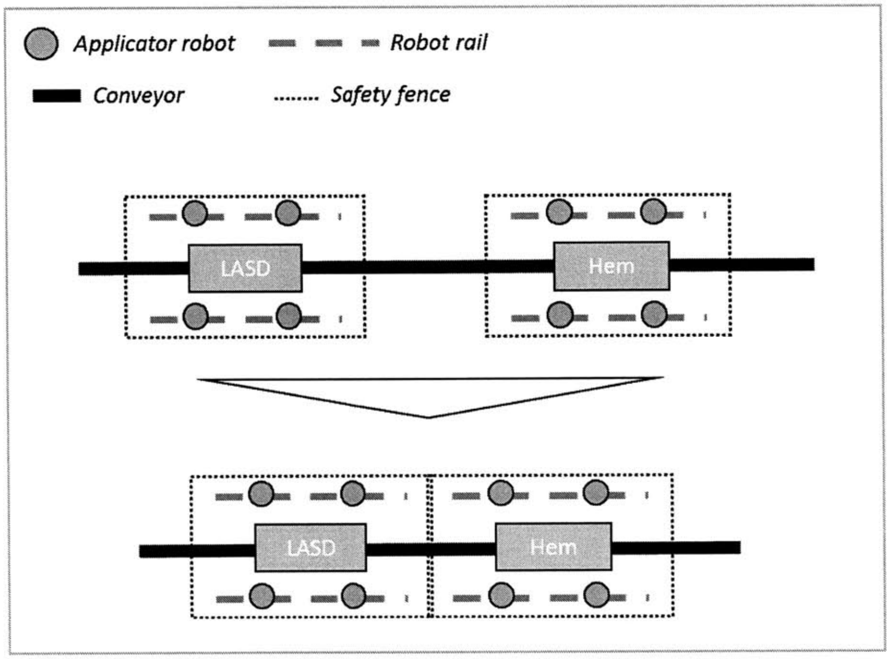


Figure 4-10: Diagram for compressed cell concept

and can conflict with visual inspection systems.

Overhead UBS Lift - This approach is very similar to the UBS lift method, except it utilizes a common type of overhead carrier that both translates forwards and backwards and also raises and lowers the vehicle. While this is common equipment that can cost less than the current approach, and eliminates a carrier return loop, it also would introduce longer indexing times.

The *Concept prioritization* phase aids in the selection of the most high potential concepts for further analysis and inclusion in full layout solutions. For this study the prior two phases result in a list of twelve, high-potential concepts. While the level of detail provided on a template is insufficient for making an investment decision, it does allow for relative ranking of ideas.

We complete the relative ranking of these eight concepts through the use of a simple chart comparing the ease of implementing an idea to its impact on the overall layout.

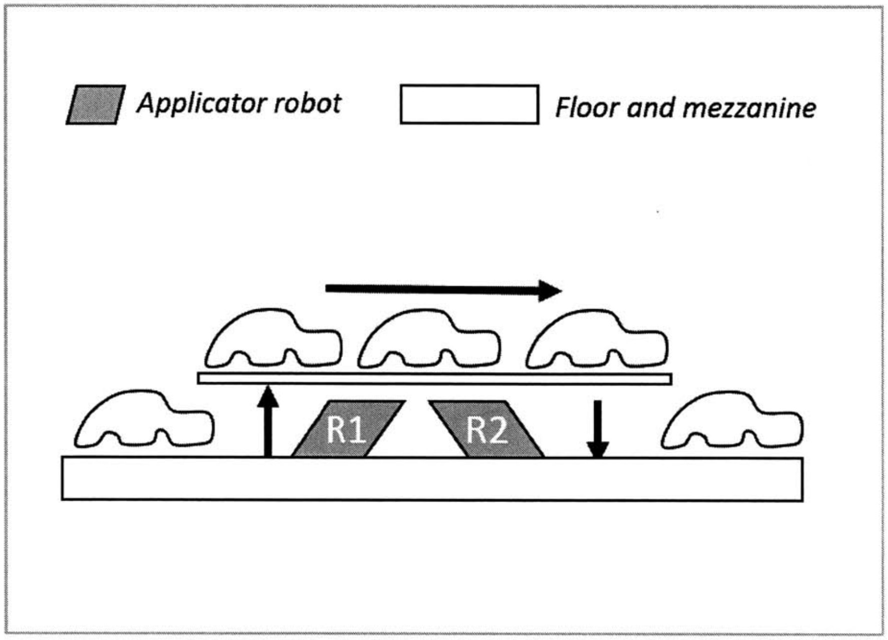


Figure 4-11: Diagram for UBS Lift concept

Each axis describes how well a concept displays a desirable trait. Concepts with the highest impact rank high on the vertical axis, concepts that are very easy to implement rank farthest to the right on the horizontal axis. The most desirable concepts cluster in the upper right corner of the diagram. The baseline concept reflects the current approach to sealing cells. We set ease of implementation at 4.0 and impact at 3.0 for the baseline.

Within the impact category we assess cost, footprint impact and impact on processing time. Each concept is rated from 1 (low) to 5 (high) along each subcategory and the overall impact is a weighted average.

If a concept costs less, saves space or reduces processing time against the baseline, we assign it a higher score than the baseline (3.0 for the baseline solution in this case). For example, the *Cell stacking* approach would score 2 in cost as it costs more than the baseline. But, it would score a 5 in footprint reduction as it greatly reduces space and a 4 in processing time as it reduces overall vehicle processing time. We assign equal weights to each category, so the *Cell stacking* option scores a 3.6 in impact: $\frac{1}{3} * 2 + \frac{1}{3} * 5 + \frac{1}{3} * 4 = 3.6$

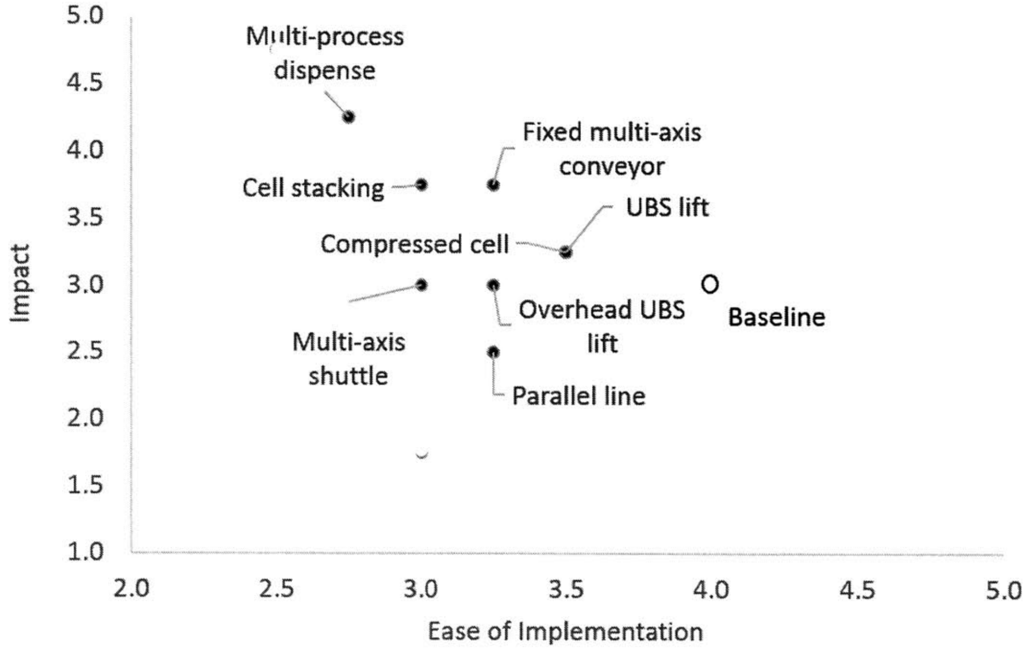


Figure 4-12: Comparison of ease of implementation and impact for eight concepts under consideration

We use the same methodology for *Ease of implementation.* Except, the key subcategories include development time, development complexity, safety and maintenance implications. If a concept improves upon the baseline in any of these areas, it receives a higher relative score. If a concept underperforms versus the baseline in any of these areas it receives a lower relative score.

For our purposes we assign equal weights to each metric in the impact category. However, we assigned a slightly heavier weighting to safety in the ease of implementation category as sacrificing safety for performance is an unacceptable trade-off.

The first iteration of scoring compares each potential concept to the baseline. Through subsequent discussion with subject matter experts, we produce iterations that simultaneously rank options against each other and against the baseline. For example, *Overhead UBS lift* and *Parallel line* both utilize common technologies. However, *Overhead UBS lift* saves more space and costs less than the parallel line approach. This process continues until we reach a consensus on relative performance and scoring between all concepts.

From this ranking we can identify the highest potential individual concepts and focus on these areas for developing full layout solutions. We select any option that scores above a 3.0 in both categories. This indicates that the concept outperformed the baseline in at least the *Impact* category. As a result of these comparisons, we select the following options for solution development.

- Multi-process dispense
- Fixed multi-axis conveyor
- Cell stacking
- Compressed cell
- UBS lift

4.2.5 Summary of Research and Analysis Phase

During this section we've reviewed the approach by which we document and understand the baseline system and sources for new sealing concepts. We then discussed how we assess each concept and prioritize them for further investigation. The goal here, was to conduct enough research into each concept in order to complete relative rankings. This helps us make efficient use of engineering resources by not expending detailed efforts on concepts that underperform versus the alternatives.

The prioritized concepts serve as the "ingredients" for a full layout solution. During the next section, we will discuss how we group these ideas into full sealing line layouts, investigate them in further detail and progress towards our space and cost reduction objectives.

Chapter 5

Solution development and refinement

5.1 Solution development

In the prior section we discussed how we develop a list of high potential concepts that could aid the achievement of our cost and space reduction targets. This section will discuss how grouping those concepts into full layouts can translate into multiple solutions. We will also discuss how we down select from three high-potential layout solutions, to a final recommendation. Again, we practice an approach that only gathers the details necessary to make relative comparisons and move on to the next phase. This continues to conserve some of the most in-demand resources (layout teams, cost-estimation resources), until absolutely required.

5.1.1 Grouping of concepts into high potential layouts

The concepts developed in the prior sections represent discrete ideas for reducing space and cost requirements for one or more sealing processes. However, in some cases, we can realize superior benefits through a combination of concepts.

Throughout this phase we produce multiple combinations of high-potential concepts. For each iteration we build a high-level layout, like the one shown in Chapter 4. The iteration cycles allow us to observe which concept combinations show the greatest floor-space reductions.

This approach is largely procedural. We design layouts, test them with a group of subject matter experts, then incorporate their feedback and move on to the next version. These sessions help identify potential throughput, processing, maintenance and safety issues. If an idea shows promise, but the team expresses concern in an area, we conduct some rough estimates of capability.

Appendix B shows several of the layout iterations used throughout the analysis along with primary considerations for eliminating a layout as an option. In general we eliminated solutions as on option for one or more of three reasons.

1. The layout iteration does not comply with maintenance requirements such as three-crew, three-shift enablers - this is described in detail later this chapter
2. The layout iteration generates a high risk of not meeting shop rate
3. The layout iteration does not deliver adequate space savings, or alternatives showed much more promise

Overall, this iterative process with GM's experts leads to three high potential layout solutions. We select these three for further consideration because they do not display any of the three deficiencies mentioned above and also show promise in terms of space and cost reduction.

First, let us review the baseline layout in Figure 5-1 below. The vehicle enters from the left into a manual seal zone. If operators detect no defects the vehicle body travels along via an underbody skid to the next zone. At this location the vehicle is transferred to an overhead carrier for the underbody sealing cells. In these locations, the bottom of the vehicle must be exposed in order for the automation to reach all necessary seams. After UBS 1 and 2, the vehicle goes through an inspection station before returning to the same skid.

The line splits into a parallel configuration for ISS, LASD and HEM in order to achieve adequate line rates. Vehicle bodies then proceed through inspection to elevators that raise the vehicle to overhead transfer lines. The raised transfer lines then reorient the vehicle and lower it to floor level for the final sealing stages. After Cosmetic seal, Manual seal 2, and Anti-chip the vehicle receives a final sealing inspection and moves on to the next phase.

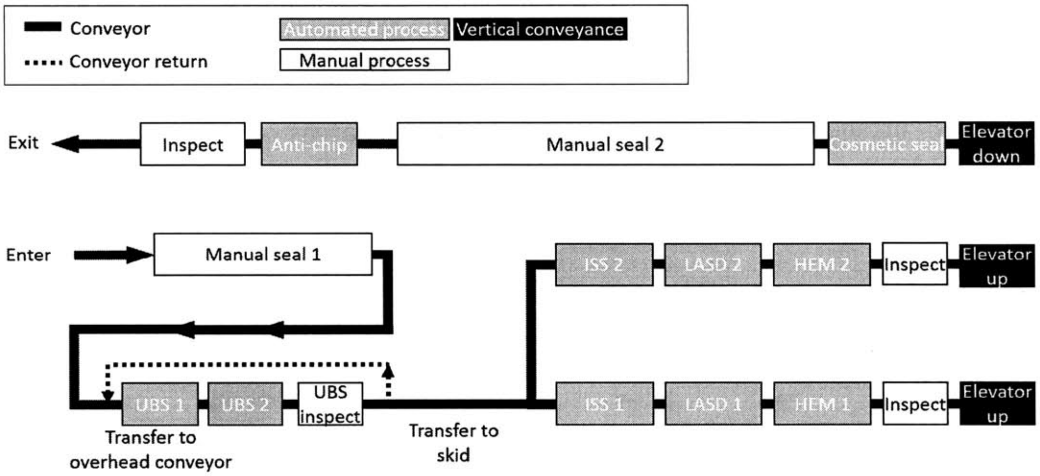


Figure 5-1: Current layout of baseline facility

The next three layouts in this section will cover the solutions that we consider for the final stage of the project, refinement. We will provide an overview of each of the three layouts, then proceed to discuss the relative merits of each.

Solution A, our first high potential solution utilizes stacked cells and multipurpose tooling. Solution A utilizes much of the baseline approach's layout philosophy. However, we pair UBS with LASD through the use of a stacked cell arrangement. This stacked cell uses automation on two levels, a ground floor and a mezzanine level. While ground floor automation completes the UBS processing, mezzanine level automation completes LASD processing.

The layout continues with a split line approach for ISS and HEM. These cells utilize tooling capable of ISS and HEM sealing. Through the addition of this flexible tooling and additional automation in the cell, initial estimates show we complete both processes within the appropriate takt time.

The final modification occurs with a stacked anti-chip, roof ditch and cosmetic cell. This arrangement leverages the existing anti-chip cell with overhead mounted roof ditch and cosmetic robotics. This cell requires a slight modification to the order of operations for the sealing line, so a manual seal station is combined with inspection at the end of the sealing line. We have no concerns with throughput for this cell as it utilizes the same amount of automation as if we had independent processes. Also, the risk of interference is very low as the application surfaces for each process are on different areas of the vehicle.

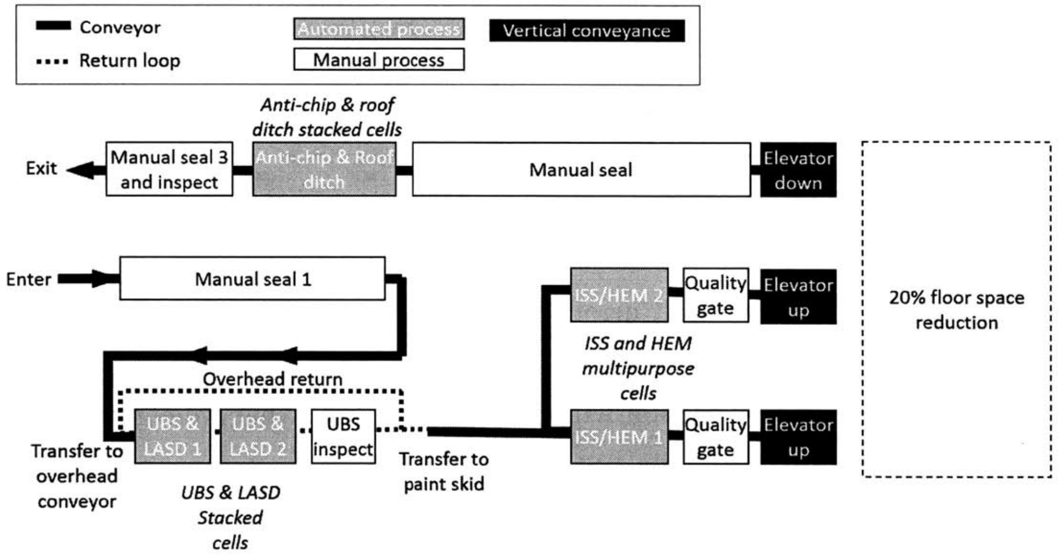


Figure 5-2: Layout for Solution A

The combination of these two stacked cell designs and multipurpose tooling enables a roughly 20% decrease in floor space and the removal of six robots from the baseline configuration. The in-line approach for LASD allows for the removal of one LASD robot from each cell by sharing workload between cells (in a parallel design the two LASD cells cannot share workload). While removing two processing robots in some cases may create capacity constraints, in this case it does not. Running six LASD robots in a series arrangement still meets rate and in fact has leaves approximately 25% of its sealing capacity unused. The parallel approach in the baseline solution required these two extra robots in order to enable the cell to run at full rate even if one robot on either side went down (robots on the left side cannot access surfaces treated by robots on the right side).

The ISS/HEM approach eliminates the need for two robots per cell through workload sharing (total of four removed from baseline). However, the ISS/HEM cells introduce new and unfamiliar tooling. Also, while initial analysis shows the ISS/HEM station can complete processing within the desired takt time, we must take a closer look at the process steps and assumptions in order to confirm that the process performs at an acceptable rate. The table below shows how we compare the before and after capability of the HEM and ISS processes.

Process Name	Maximum rate	Required rate	Unused capacity
ISS	100	63	37%
HEM	75	63	16%
ISS/HEM	65	63	3%

Table 5.1: Process capability of ISS/HEM versus ISS and HEM independently (scaled time data)

We can see from the data above, that while the proposed design may meet rate, it will have very little ability to accommodate increases in sealing content. A mere 3% increase in the amount of sealer required would require the addition of an extra automation cell. Now, if workload sharing within the cell were an option some of this could be mitigated. But, when we look at the workload across each robot in the ISS/HEM cell, we see a fairly even workload and each robot is highly utilized.

Robot	Workload (Time)	Time available	Unused capacity
Vision/HEM 1 and 2	137	142	3%
HEM/ISS 1 and 4	134	142	5%
HEM/ISS 2 and 3	133	142	7%

Table 5.2: Processing time of each robot within ISS/HEM cell (scaled time data)

While Solution A shows promise in terms of cost and space reduction, it does so with some throughput and technology risk.

Solution B makes use of multiple installations of high flexibility conveyance systems to complement existing cell designs. The figure below shows the hypothetical layout for such a solution.

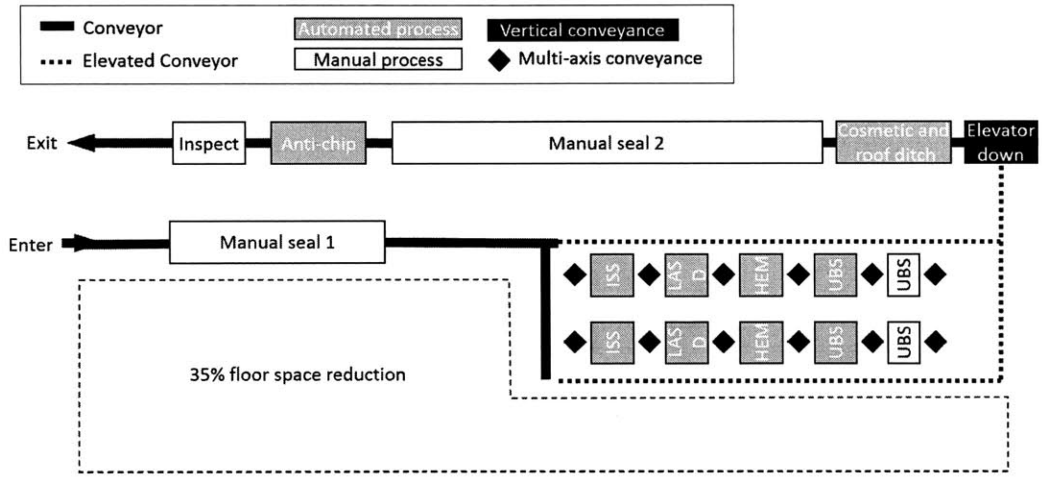


Figure 5-3: Layout for Solution B

The fixed multi-axis conveyance systems in this approach take up less space and allow for new cell orientations on the line. The result is an approximately 35% reduction in floor space. At the start of ISS, the conveyance will lift the vehicle from its underbody skid and place it in the cell for processing. At the end of a cycle, the vehicles simultaneously index to the next cell via a multi-axis conveyor between each cell. At the completion of the UBS inspection phase, the vehicle is returned to its original underbody skid on a raised conveyance line and then transferred to the next section of the sealing line which remains unchanged from the baseline.

This solution has the benefit of removing the overhead conveyance system along with multiple elevators and turntables. However, like with Solution A, we identify some throughput risks. The multi-axis conveyor has a slower index time than a single axis-conveyor. In general, the multi-axis conveyor takes almost 70% longer to transfer a vehicle. So we must run further analysis to determine if the new line can meet the shop's rate requirement. Table 5.3 shows this analysis for the HEM cell which we already know is heavily utilized based on the data in Table 5.1.

Conveyance	Takt time	Index time	Available time	Required time	Utilization
Single axis	155	21	134	113	84%
Multi axis	155	36	119	113	95%

Table 5.3: Processing times for HEM cell with single and multi-axis conveyance (scaled time data)

We see that the HEM cell faces a high utilization with the use of the multi-axis conveyance. In order to confirm that the multi-axis conveyance does not create similar risks for the other processes, we complete the same analysis for the other steps as well. The calculation below is (Processing time + index time)/ takt time.

Station	Single-Axis	Multi-Axis
ISS	63%	73%
LASD	48%	57%
HEM	84%	95%
UBS	62%	71%

Table 5.4: Cell utilization under single-axis and multi-axis conveyance conditions

Our analysis confirms that each station maintains adequate capacity, with the exception of the HEM station. We do not need to run the analysis for anti-chip nor cosmetic/roof ditch as these cells remain identical to the original design.

It should also be noted that we base capacity values on the next vehicle that will be assembled at this facility. The extra capacity at construction is effectively a real option for GM to assemble vehicles with higher sealing content in this facility. Also, some of the capacity stems from the requirement to enable the line to run full rate with any one robot down in a cell (part of the aforementioned 3-crew/ 3-shift requirements).

Solution C is a multi-concept hybrid. It utilizes a compressed cell design, two types of stacked cells and the multi-axis conveyance. We design this layout to try and leverage the advantages of the different cell and line concepts in a manner that either avoids or reduces the impact of their deficiencies.

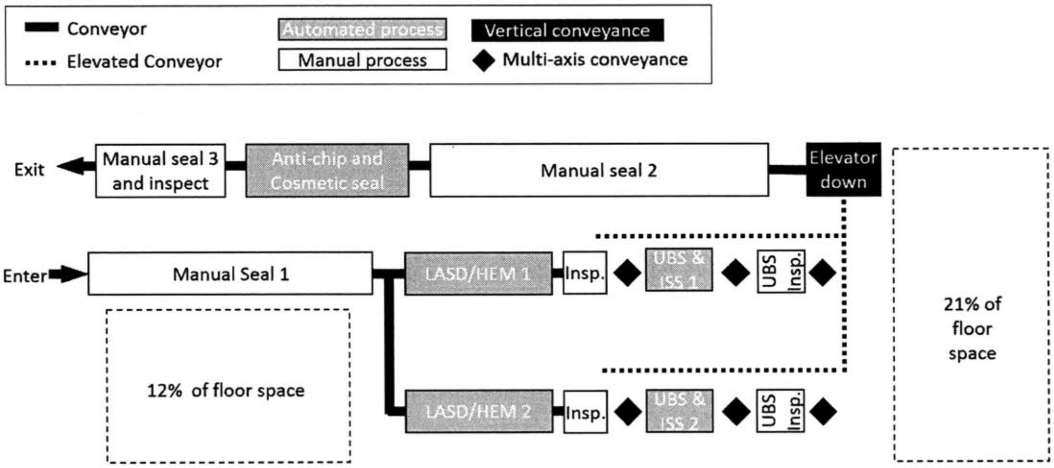


Figure 5-4: Layout for Solution C

The line begins much like Solution C with a manual seal station. A split line starting with compressed LASD/HEM cells lead off the automated section. As we saw with the time analysis in Table 5.4, HEM represents the greatest throughput risk. The LASD/HEM cells use single-axis conveyance, so we maintain an appropriate utilization level. Also, the compression uses the same amount of automation and two separate work zones (one for LASD and one for HEM) so we have no increased throughput risk.

The next section utilizes a combination of multi-axis conveyance, stacked cells and a raised conveyance line. UBS and ISS pair well as they share material. They pair well with multi-axis conveyance too, as their utilization stays at a manageable level even after accounting for the additional indexing time (reference Table 5.4). As with Solution B, the elevated line eliminates the need for several elevators and turntables. The process finishes in the same manner as Solution A. Again, an adjustment in the order of operations requires moving some manual steps after the final automation station. Throughput for the combined Anti-Chip, Roof-ditch and Cosmetic cell is the same as if the cells were independent. The robots do not interfere with each other and the the total number of robots dedicated to each process remains the same.

This approach achieves strong space reductions and has potential for cost reductions as well. It does not show any of the throughput risks of other solutions either. However, stacked cells do carry additional costs as they require far more support structure than a single level cell.

5.1.2 Downselection process to primary solution

In order to fully justify a recommended solution, we must complete a strategic assessment, cell designs, engineering layouts, process simulations and cost assessments. However, we can begin to identify the highest potential concept through a strategic assessment, which doesn't require the same level of engineering time and resources as the other analyses. In order to make the most efficient resources with this study, we use a strategic assessment of the three solutions in order to identify the highest potential option.

The criteria involved in the strategic analysis include:

- 3 crew - 3 shift enablers: this studies how well a layout can support a three-shift production schedule, running Monday through Saturday. A key requirement for this enabler is the ability for maintenance to occur while the line runs and still meets overall shop rate
- GMS scorecards and lean system design criteria: this assessment uses General Motor's Global Manufacturing System to evaluate the efficiency and capability of the layout
- Risk assessment of all systems: The risk assessment identifies all safety risks associated with the design, and helps us understand how to avoid those risks
- Impact vs. ease of implementation comparison: Using similar criteria to that described for the concept comparison, we compare the overall solutions in terms of impact and ease of implementation

The table below summarizes the key findings for all three solutions. We see that all three meet 3-crew/3-shift requirements.

Criteria	A	B	C
Does each cell run full rate with one robot down?	Yes	Yes	Yes
Is it safe to run the line during routine maintenance?	Yes	Yes	Yes
Is there aisle access to all equipment?	Yes	Yes	Yes

Table 5.5: Summary of 3-crew, 3-shift capability of potential solutions

As the 3-crew, 3-shift analysis does not eliminate any options, all three proceed to the next step in our analysis. A review of each layout using GM's lean scorecard.

Metric	**Solution A**	**Solution B**	**Solution C**
Lean criteria 1	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 2	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 3	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 4	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 5	◕ Outperform	● Strong outperform	● Strong outperform
Lean criteria 6	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 7	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 8	◕ Outperform	● Strong outperform	● Strong outperform
Lean criteria 9	◕ Outperform	● Strong outperform	● Strong outperform
Lean criteria 10	◕ Outperform	◔ Acceptable	◔ Acceptable
Lean criteria 11	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 12	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 13	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 14	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 15	◕ Outperform	● Strong outperform	● Strong outperform
Lean criteria 16	◕ Outperform	● Strong outperform	● Strong outperform
Lean criteria 17	● Strong outperform	◕ Outperform	◕ Outperform
Lean criteria 18	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 19	◔ Acceptable	◔ Acceptable	◔ Acceptable
Lean criteria 20	◔ Acceptable	◔ Acceptable	◐ Equivalent
Overall	6	8	9

Figure 5-5: Scorecard for evaluation of each solution against baseline

Each line in the scorecard represents one of the lean criterion used by GM to evaluate the lean performance of a manufacturing facility. These criteria include things such as flexibility, safety and number of station connections. For our purposes we again use relative instead of absolute performance measures. Fully shaded circles show the solution strongly outperforms the baseline while each increment of reduced shading shows outperform, equivalent and unacceptable performance respectively. We allocate +2 points for a strong outperform, +1 point for outperform, 0 points for equivalent, -1 point for acceptable and -2 points for unacceptable. Overall, we see all three solutions show advantages on the lean scorecard, but Solution C has the best overall performance.

Our risk assessment utilizes an in depth safety audit called "G-risk" This system features 300+ questions designed to identify potential safety risks in any proposed manufacturing installation. We summarize the key findings for each solution below.

For *Solution A*

- Stacked cells create access challenges for maintenance personnel
- Stacked cell arrangement create fall hazards
- Stacked cell design requires means of access for tasks that cannot be completed at floor level
- Stacked cell design requires new safety systems for operator to be in the cell during robot application path refinement operations

For *Solution B*

- UBS cell and multi-axis conveyance have service tasks that cannot be performed at floor level
- Maintenance can require heavy lifting of system components
- Shared safety gates between cells requires safety systems in each cell to integrate with each other

For *Solution C*

- Stacked cells create access challenges for maintenance personnel

- Maintenance can require heavy lifting of system components
- Stacked cell design requires new safety systems for operator to be in the cell during robot application path refinement operations
- Shared safety gates between cells requires safety systems in each cell to integrate with each other
- Stacked cell arrangement creates fall hazards

The intent of this review is two-fold, the first objective is to help us identify any insurmountable safety challenges. Fortunately, the cells and designs used for all three solutions do not represent any safety risks that cannot be addressed through properly engineered designs and operating processes. For instance, access can be improved to stacked cells through the installation of mezzanines with safety rails. We can mitigate heavy lifting with the installation of cranes. However, both of these concerns feed into the second objective of the risk assessment.

The second objective is to raise awareness of the risks that will require an investment in the design and installation of the cells. Based on the G-risk assessment, we see that the stacked cell arrangements in particular, will require substantial investment in safety systems. Also, the multi-axis conveyance drives the need for equipment to lift heavy components. We keep this in mind for the purpose of estimating the cost and complexity of a potential solution.

We close this phase of analysis with a similar relative ranking approach to the one used for our concepts in Chapter 4. We complete a relative ranking of the three solutions in terms of ease of implementation and impact.

We rank the impact of Solution A the lowest. It demonstrates the lowest footprint savings (20%). This low footprint savings and the minimal impact on conveyance reduction offset some of the savings derived from removing automation. Solution B has the next best impact, as it demonstrates great footprint reduction opportunity (35%). However, it utilizes twelve multi-axis conveyance systems. These systems carry a high price tag and will offset

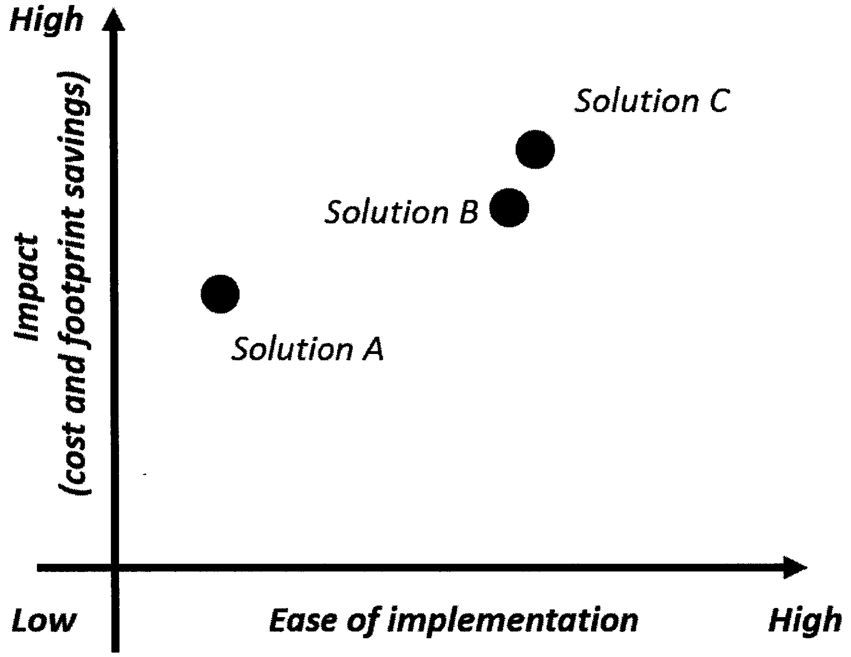


Figure 5-6: Ease of Implementation vs. Impact for the three layout solutions under consideration

some savings derived from other conveyance and floor space reductions. Solution C demonstrates the highest impact as it achieves strong floorspace reduction levels (33%) with fewer multi-axis conveyors. It also eliminates a large amount of linear conveyance, elevators and turntables.

We rank Solution A lowest in terms of ease of implementation. This is due to the potential complexity of multi-purpose tooling. Solution B has similar, but slightly lower ease of implementation compared to Solution C. We attribute the marginal difference due to a qualitative assessment with subject matter experts. The clustering approach of this layout would require potentially larger redesigns of existing cells than Solution C.

As a result of this last relative analysis, we find that Solution C shows the highest reward among options, but not without risk.

Compared to solutions A and B, Solution C shows the highest potential for floor space reduction, highest potential for cost reduction and best overall strategic performance. It also demonstrates the lowest throughput risk.

We should also note that this project is intended to support future investigations for GM as well. Selecting Solution C pushes the team to explore a broader variety of cell designs. This means the project covers more material and can deliver analysis on a broader set of options to GM.

5.2 Recommended solution and final analysis

While the strategic analysis helps identify the highest potential concept, we must still quantify the advantages of the proposal. These activities, listed below, help remove uncertainty with regard to final performance of the system.

- Cell designs
- Engineering layout development
- Process simulation
- Cost analysis

The next four sections will review the approach for each of these analyses and their associated results. We will also discuss some of the primary trade-offs uncovered through this analysis and how we address those issues through proper system design.

5.2.1 Cell designs

For the purposes of this analysis, a completed cell design is not intended to provide a detailed 3D engineering model, but rather to highlight modifications to existing designs and address feasibility concerns of the proposed solution.

In particular, each cell design documents two key parameters for the system. First, it confirms clearances and second, it confirms accessibility.

With regard to clearances, the designs highlight the locations of key support structures, conveyance and automation. This analysis typically leverages an existing cell design and highlights modifications to the design. Using this methodology we can avoid rework in the design and take advantage of the already defined clearances in existing designs.

With regard to accessibility, we assess the design based on two needs. First, the operators and/or robotics must have clear access to the surfaces receiving sealing treatments. Second, maintenance technicians must have a safe and accessible path to work on automation. As with the clearance analysis, we use the locations of automation, support structures and conveyance to complete this analysis. Additionally, we examine vehicle orientation and positioning method. The vehicle orientation serves to aid our understanding of how easily an applicator can reach a sealing surface. The positioning method also carries importance from a safety and maintenance perspective. The positioning method must be able to hold the vehicle in place even in the case of a loss of power. This makes it safer for a maintenance technician to work around an active cell.

These cell design analyses serve to identify and remove risks from the proposal. As such, they utilize a combination of illustrative figures to highlight changes from fully detailed existing cell designs. The figure below serves as an example and highlights the work zones for each robot during each step of the process. It shows how the system avoids spatial interference and the locations of each piece of automation and rail systems.

Step 1, in the top left, shows robots 1-4 completing sealer application tasks in different regions on the vehicle, while vision robots complete part locating tasks. Step 2 shows where each robot moves after the completion of step 1. Four floor mounted robots work on the doors, while two overhead robots work on the engine compartment and the trunk. Steps 3 and 4 show how the cell completes its tasks my mirroring the operations completed in steps

1 and 2 on the remaining vehicle panels. Final engineering designs and 3D simulations would come later in the seal line development process, after GM has made an investment decision and selected an implementation location.

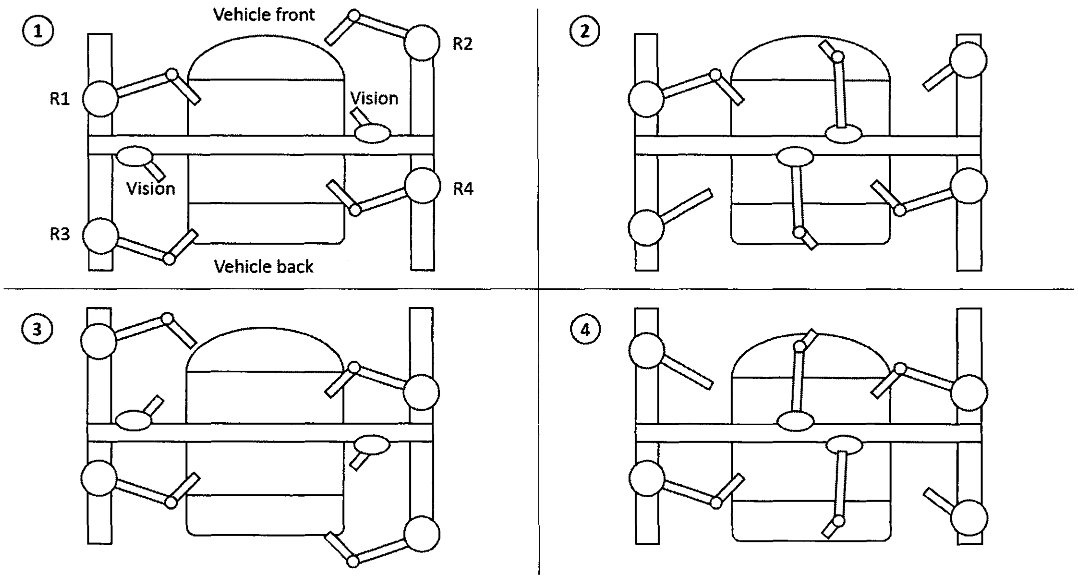


Figure 5-7: Example of a figure used to illustrate automated cell design and process

The recommended solution uses three cell approaches outlined in Chapter 4.

- Compressed cell - LASD and Hem
- Stacked cell - UBS and ISS
- Stacked cell - Anti-chip, roof ditch and cosmetic

This Compressed cell approach utilizes the existing design for LASD and HEM sealing cells. However, we remove approximately 25 feet of conveyance from between the cells. This removes a path for crossing over the line but saves length of the facility. The cell still allows for maintenance during operation as well. Maintenance zones are located at the corner of the cells that allow operators to deactivate any one robot in a cell and service it without impacting the other pieces of automation.

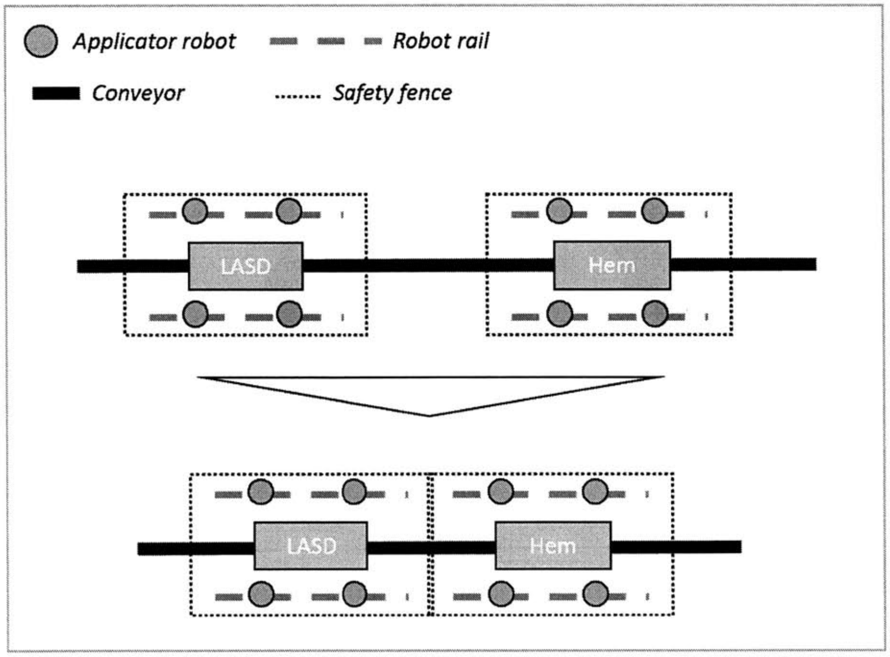


Figure 5-8: Diagram of compressed cell for recommended solution

We choose LASD for this approach as the material shows poor compatibility with other sealer materials. While the compressed cell saves space, it does not introduce any situations where the LASD material may contaminate the HEM sealing area and cause productions issues.

We choose HEM for this approach because of the heavy current utilization of the HEM sealing process. Using any conveyance other than stop station conveyance introduces a throughput risk. We also have no concerns on clearance issues, as the compressed cell design adds no additional structures and we separate the work zones for LASD and HEM within the compressed cell area.

The stacked cell for UBS and ISS is described in our next figure. The stacked cell arrangement takes two distinct processes and combines them into a single application zone. In this case we combine UBS and ISS as they share relatively similar processing times and the same material (which simplifies the installation of dispense equipment). At the start of the process, multi-axis conveyance places the vehicle on a raised fixture and moves out of the

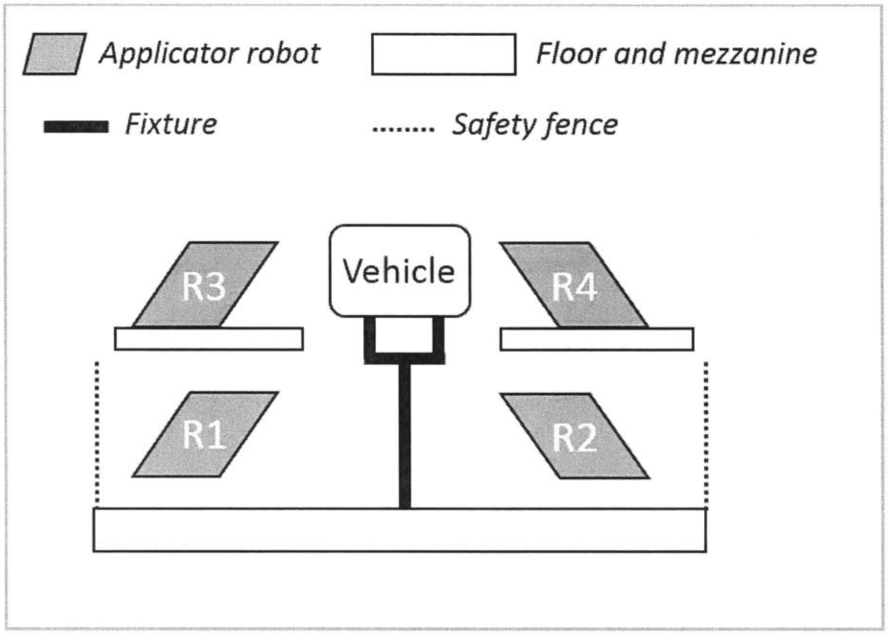


Figure 5-9: Diagram of stacked cell for recommended solution

way. Then the UBS and ISS processes occur as if they were independent steps.

The UBS portion of the stacked cell looks much like a traditional UBS cell, with floor mounted applicator robots and an elevated vehicle. However, we complement this cell with raised rails for ISS robotics and a mezzanine around the upper level to provide maintenance access. The cell design allows for both the UBS and ISS activities to commence simultaneously. UBS and ISS processes treat different vehicle surfaces, so we have no risk of robot interference for this approach.

The fixture used to elevate and locate the vehicle also enable full access to the vehicle underbody. This approach leverages another existing UBS cell design that operates without any robot clearance concerns. Additionally, the cell entrance and exit areas are set wide enough apart to accommodate the multi-axis conveyance loading and unloading processes.

The advantage of this cell design on its own is actually quite small. The design requires four UBS robots instead of the three in the baseline and drives a need for elevated structures. While on its own, the cell design saves approximately 5% of floor space, the overall design likely costs more than the two cell equivalent. However, when we incorporate this cell with a revised layout philosophy in the next section, we'll see how it enables important space savings and cost reductions.

Finally, for our Anti-chip, Cosmetic and roof ditch cell, we use a variation of the stacked cell arrangement. While this approach uses a stacked cell as well, it requires fewer structural enhancements. The vehicle remains on a traditional skid conveyor on the floor.

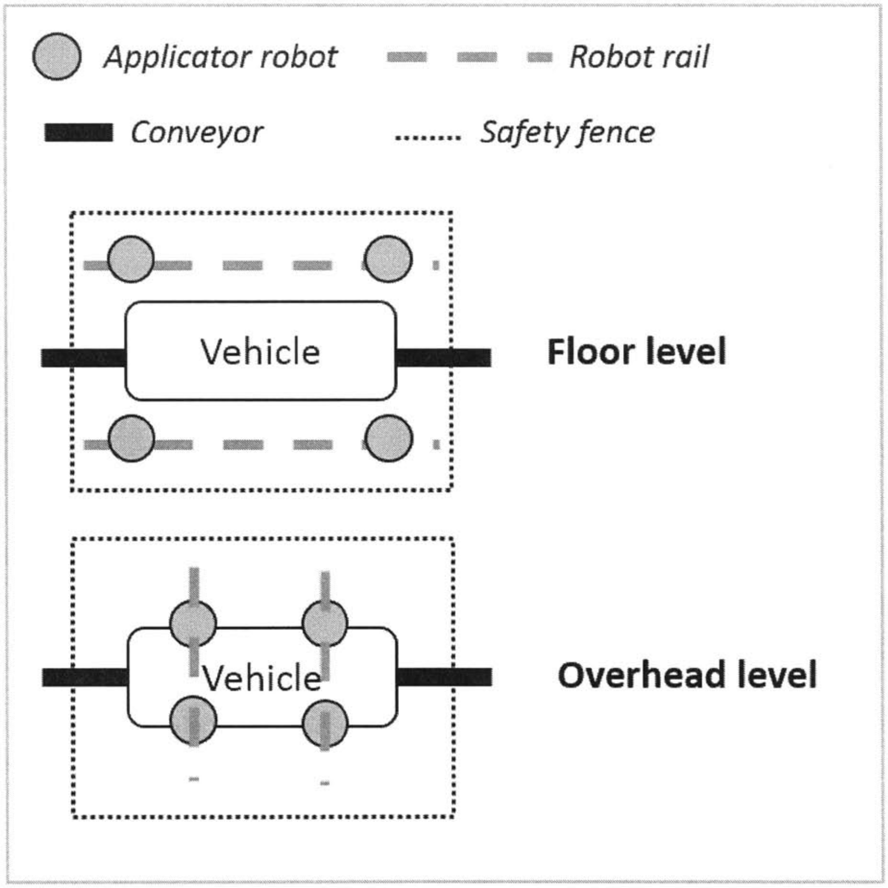


Figure 5-10: Diagram for Anti-chip, Cosmetic and Roof Ditch stacked cell

The floor level of the cell is arranged like a traditional Anti-chip cell with four robots, two on each side. However, cross beams over the top of the cell allow for mounting four additional robots. Two of these overhead mounted robots complete cosmetic sealing and two complete roof ditch sealing. All robots are mounted on rails to allow them to slide laterally out of the work zone and receive routine maintenance.

This cell design utilizes existing practices for mounting overhead applicator robots. Leveraging existing approaches means we can confirm that the cell allows adequate clearance for the vehicle to enter/exit and for the robotics to complete their tasks. Also, each robot operates in a separate application zone, so robot interference is not a concern.

This cell approach also reduces footprint by about 5%, but the processes involved can utilize a far simpler and less expensive structure than in the UBS/ISS arrangement. So, in isolation, this cell can offer solid benefits in terms of space reduction and cost savings derived from a smaller building footprint.

5.2.2 Layout development

For the final space saving assessment we create an engineering layout based our baseline paint shop. To complete this process we utilize the existing designs and start by removing the equipment deemed unnecessary by our design. We then proceed to modify existing cell layouts to match the footprints of our solution's automated cells. Finally we reinsert these modified cell, conveyance and equipment layouts into the overall shop layout and connect them via the appropriate conveyance systems.

In the prior section, we identified how new cell designs on their own could produce only marginal gains. However, it is important to understand how these new designs, combined with more flexible conveyance and a revised layout approach can introduce major gains. We'll introduce these impacts one at a time.

First, the stacked UBS/ISS cell in a parallel line design eliminates the need for the entire section of conveyance in the lower left section of the layout design. When we couple the stacked cell with multi-axis conveyance, we also eliminate the need for a separate overhead conveyor. Eliminating the overhead conveyor not only takes out a length of conveyance, but also takes out return loops and carriers.

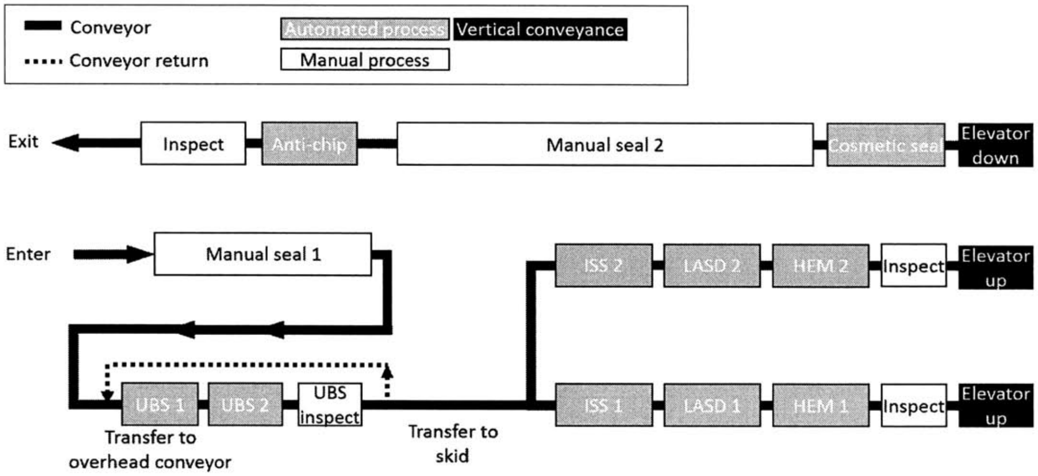


Figure 5-11: Baseline layout

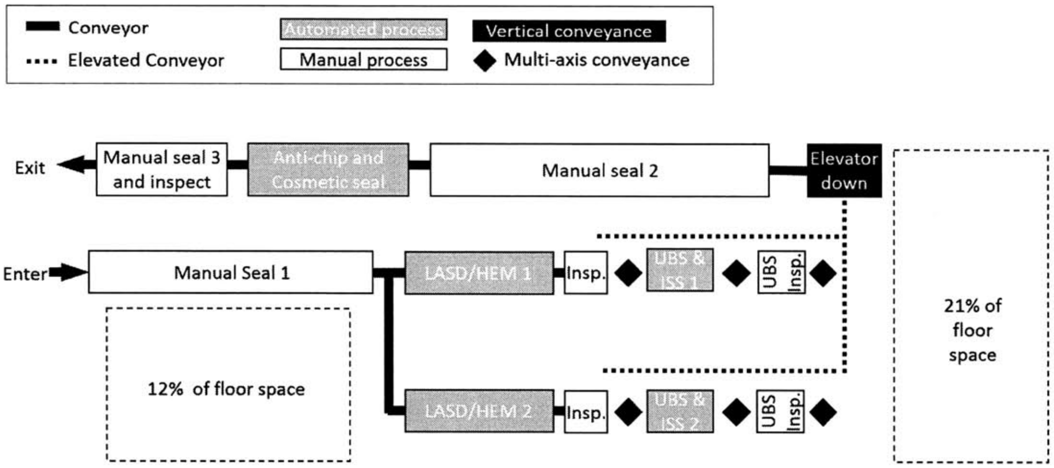


Figure 5-12: Recommended layout

Second, the compressed LASD/HEM cells impact the entire width of the manufacturing area. By shortening the length of these cells we also enable shortening of the final stretch of conveyance (shown at the top of the diagram). Of course, this could only be accomplished in combination with the stacked Anti-Chip, Cosmetic and Roof ditch cell. Once again, the combination of these approaches yields larger gains than they would independently.

Finally, by taking greater advantage of the multi-axis conveyance's flexibility we can eliminate multiple single purpose types of conveyance. We use the multi-axis conveyance to not only move vehicles between cells, but also raise them on to elevated conveyance lines. The multi-axis conveyance in combination with the cell designs, allow us to remove an overhead carrier system, four vertical lifts (two for the overhead carrier and two at the end of the parallel line), three turntables and 50% of the overall system conveyance. Overall the final engineering layout shows us that the recommendation reduces sealing line footprint by 33%

Together, the cell designs and conveyance decisions enable large space savings and conveyance reductions. However, the layout must complement the capabilities of the equipment. If, for instance we used a floor mounted skid conveyance line alongside the UBS/ISS stations, we would waste the ability of our equipment to move a vehicle vertically. Additionally, space reductions in one section of the line, must be complemented by reductions in another section. It does little good to shorten the length of our parallel line at the bottom of the layout, if the line at the top of the diagram extends 100 meters longer than the overall line length at the bottom of the diagram.

This phase has focused primarily on arranging processes and equipment in order to minimize the total space required by the line and reduce overall costs. However, we also complement this analysis with simulations to ensure the line can run at the rates required by the overall shop.

5.2.3 Process simulation

During the baseline documentation phase we walked through how we document and understand the overall throughput performance of the existing sealing line and paint shop. For the final process simulation we conduct an identical analysis with updated station parameters. Again, these included:

- Station speed
- Stand alone availability
- Stand alone throughput

- Mean time to repair

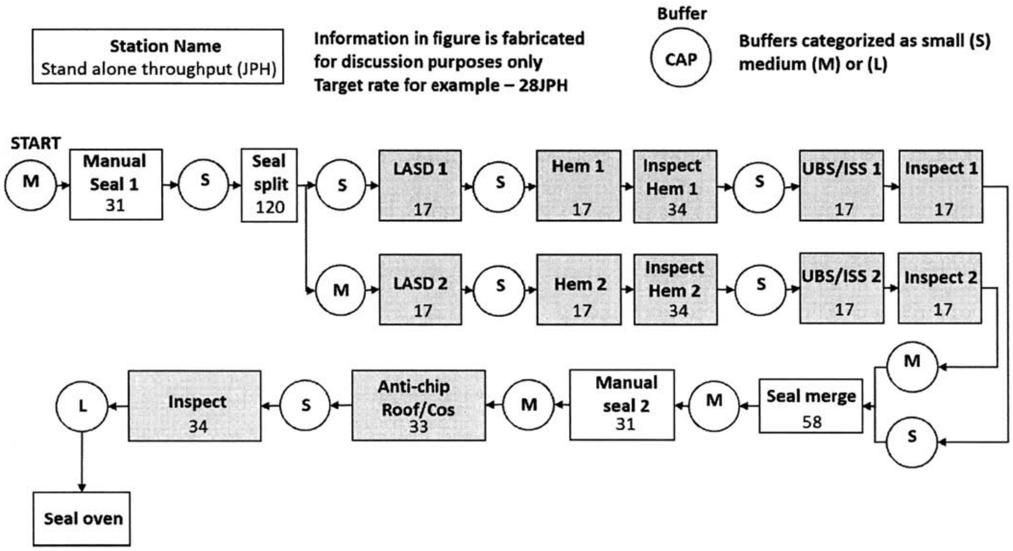


Figure 5-13: Disguised representation of throughput model for recommended solution (modified sections shaded)

As we lack actual performance data for new cell designs we make highly conservative assumptions on stand alone availability and mean time to repair. However, the new designs did utilize existing equipment with known failure rates. We utilize these known failure rates to develop the station's overall stand alone availability and mean time to repair.

The simulation for our recommended solution shows that the overall rate of the sealing line declines by 1%. However, the line still meets the required throughput rate. We also look at a simulation that accounts for interactions between the pre-treat/ELPO system, sealing line and paint line. This higher level simulation shows that the recommended layout has no statistically significant impact on overall paint shop throughput. As such, we view the rate drop as an acceptable trade-off if space and cost saving assessments show opportunity.

5.2.4 Cost analysis

For the cost analysis, we examine the recommended solutions in two areas. We first look at operating expenses and then at capital expenses.

For operating expenses we consider items such as material, labor, energy and utilities. For our analysis, we have no changes in direct labor or material usage, so these stay the same as in our baseline scenario. Also, we observe minimal changes in maintenance labor as conveyance reduction offsets a moderate increase in cell complexity. Energy and utility use represent the only major change in operating expenses. The reduced building area drives a lower air handling requirement. This reduction drives a moderate operational cost savings for the solution. But, capital cost savings dwarf the operational cost advantages of our recommended solution.

On the capital cost side we break the analysis into three categories, building, automation and conveyance.

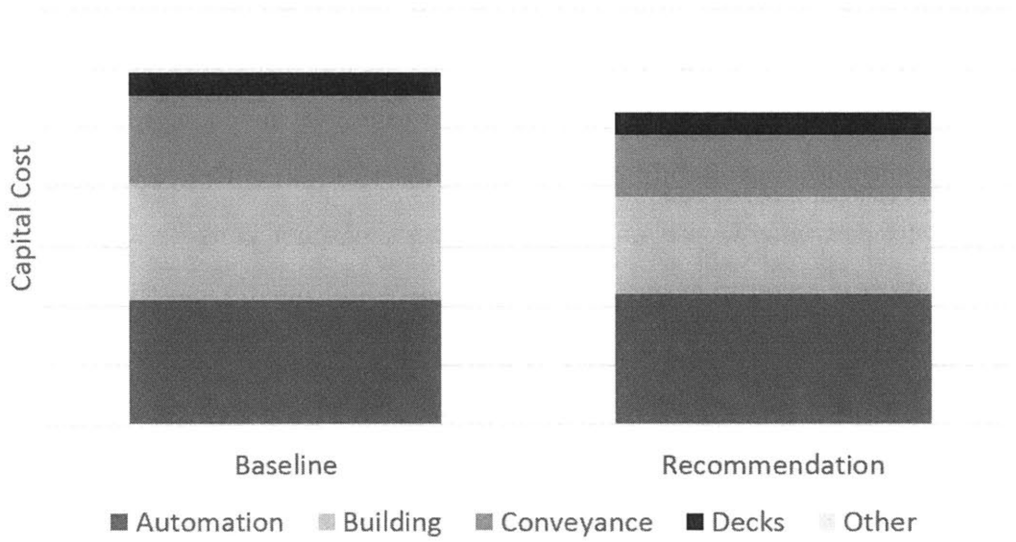


Figure 5-14: Breakdown of capital cost savings derived from proposed solution

As can be seen in Figure 5-14, the proposed solution has slightly higher automation costs but derives significant savings from both conveyance and building cost reductions. Overall, the proposed solution slightly exceeds the project's objective of a 10% capital cost reduction. This chart demonstrates once again how combining the multiple cell approaches, a new conveyance design and a layout philosophy adapted to a line's production equipment enables a significantly greater result than one would expect when analyzing any piece in isolation.

As can be seen above, the new cell designs (captured in the automation category) actually cost more than the baseline design. However, these designs enable the large reductions in conveyance and building costs that help us achieve an additional 10% cost reductions.

This project operates under the same constraints as the original line. One of those constraints includes the requirement of installing our recommendation on the second floor of a manufacturing plant. During our analysis we also find that if we install the recommended layout on the first floor, we avoid some structural reinforcement costs and achieve an additional 3% cost reduction. Again, this demonstrates that further adaptation of the layout philosophy to the equipment can achieve even greater results at a system level.

Chapter 6

Recommendations & conclusions

6.1 Final recommendation

Overall, the process we have described results in a new sealing line layout that meets the projects objectives.

- Reduces sealer line footprint by at least 25%
- Reduces capital costs by 10-20%
- Maintains or reduce operating costs
- Meets the throughput and maintainability requirements of the facility

It also meets the project's key constraints.

- Solution uses existing technology and materials
- Solution only require changes to the sealing line

Based on the performance of the recommended solution, we believe that GM should consider the solution, in part or in whole, when the next upgrade opportunity arises.

6.2 Implications for General Motors

The recommended solution, besides having a positive impact on the design of sealing lines, also has implications for the design strategy of automated cells throughout the manufacturing process.

First, the recommended solution shows a case example of the value derived from using high flexibility conveyance solutions. The conveyance system recommended in this layout, has already seen highly reliable usage in other GM facilities. The recommended layout reinforces its value and also demonstrates approaches to take even greater advantage of the conveyance system's flexibility.

Second, the solution demonstrates the value that vertical stacking of automation cells can provide to a manufacturing line. The stacked arrangement not only reduces the automation space, but also eliminates conveyance and some buffering requirements. The cost analysis also shows that even though a vertically stacked cell requires additional infrastructure investment, the building savings result in a net benefit to the facility.

And third, the full layout utilizes multiple approaches for GM to consider for future sealing line designs. This means that GM can adopt the full layout or only parts of the layout for use in future sealing line installations.

However, the recommended solution does have limitations. Specifically, most of the solution's cost savings come from a lower building construction cost. In a brownfield site with an existing building, the recommended solution will cost more than our baseline solution.

6.3 Implications for other industries and processes

We can extend the findings from this study to other industries as well. In particular, any manufacturing process that leverages highly automated system can utilize the practices in place here. If we take a look at a higher level, this project demonstrates three lean automation strategies, which yield strong results for GM and can be transferred to other applications as well.

- Intelligent reduction of conveyance systems
- Increased system flexibility
- Increased automation density

Intelligent reduction of conveyance systems supports the lean objectives of reducing transportation, inventory and motion. To achieve these reductions we showed how combining buffer analysis with new cell designs significantly reduced the conveyance needs of the system.

The project also shows how *increased system flexibility* supports the first strategy and also reduces transportation, inventory, motion and waiting. High flexibility conveyance eliminated multiple single-purpose conveyance methods. A stacked cell arrangement means a single station can complete multiple processes at once.

Finally, *Increased automation density* further aids the lean objectives of the line by identifying appropriate accessibility and density trade-offs. While this approach offered less impact than the first two strategies, it did support the overall solution's performance.

We should also acknowledge the importance of combining and optimizing these approaches together. As we demonstrated throughout Chapters 4 and 5, in isolation, these approaches may not offer adequate benefits. However, when we combine these approaches with a layout philosophy that optimizes for the strengths of each approach, we can achieve significant results.

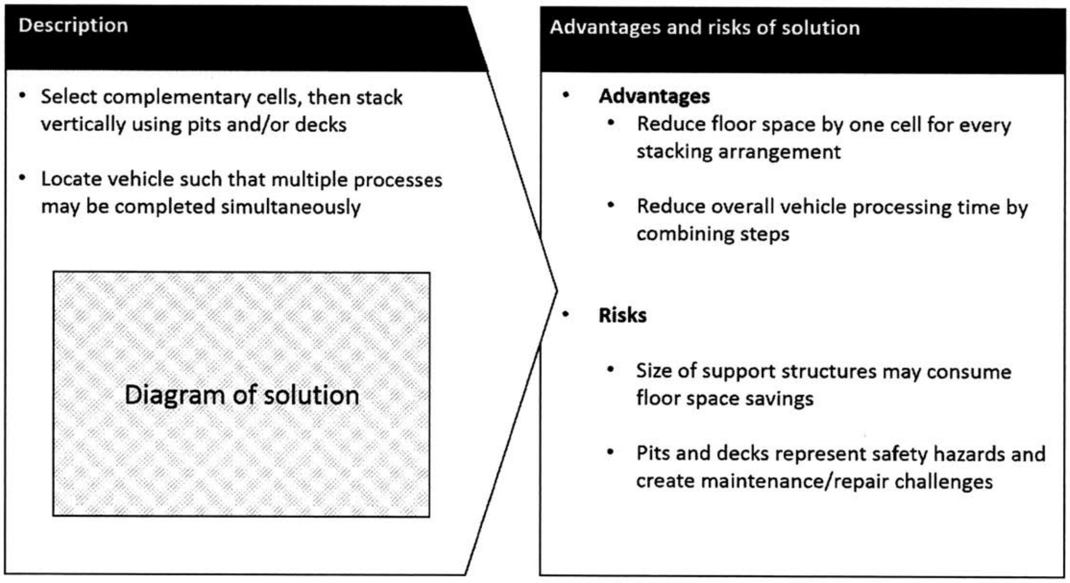
6.4 Conclusions

Overall, GM's current approach already demonstrates that lean and automation can compliment each other to create efficient high-volume production processes. This project offers a study on how further refinement of an already efficient system through lean footprint compression strategies can yield strong results.

As an output of this investigation, GM has received a set of cell designs, layouts and viability assessments to aid them in considering these approaches for future sealing line layouts. The analysis completed demonstrates the advantages associated with the recommended layout. We hope that the efforts of this project aid GM as they continue to build facilities in pursuit of their goal to *Design, Build and Sell the World's Best Vehicles.*

Appendix A

Sample templates for concept and solution evaluation



Description

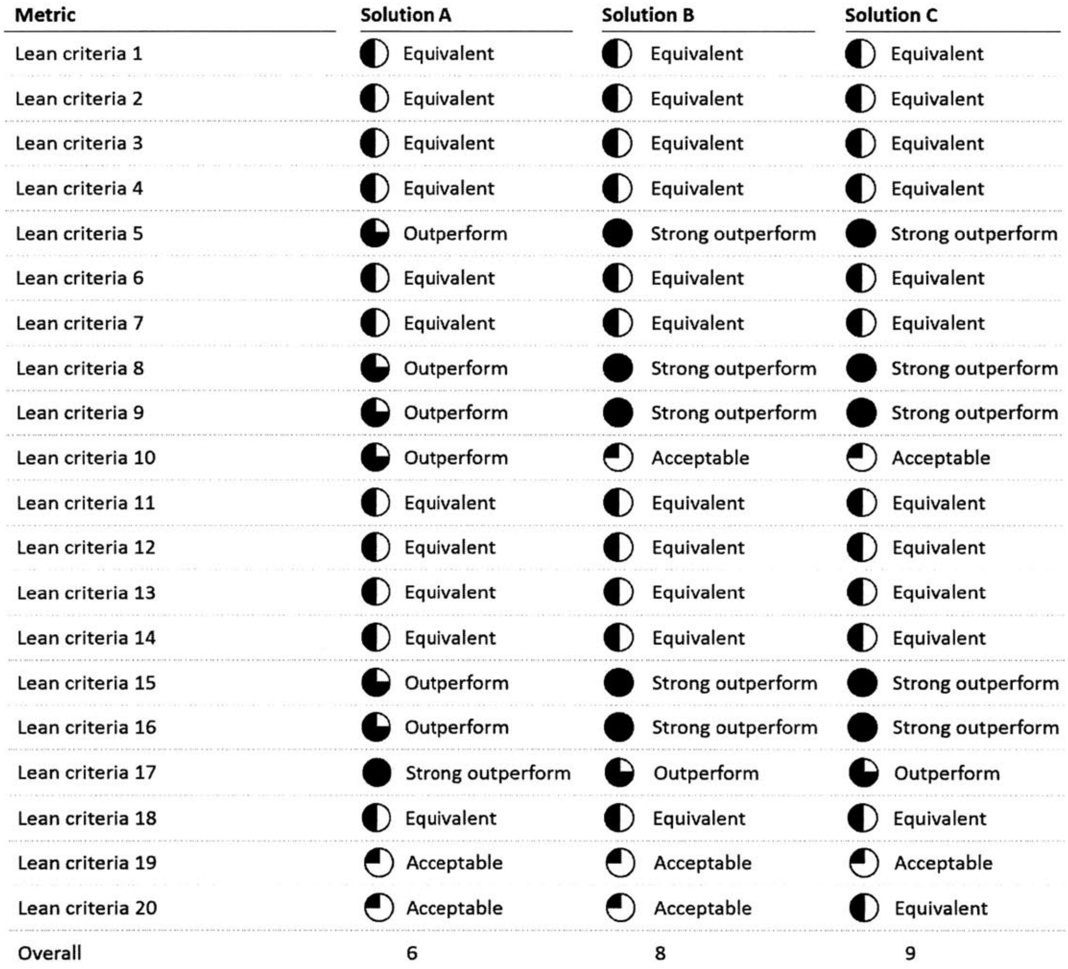
- Select complementary cells, then stack vertically using pits and/or decks
- Locate vehicle such that multiple processes may be completed simultaneously

Diagram of solution

Advantages and risks of solution

- **Advantages**
  - Reduce floor space by one cell for every stacking arrangement
  - Reduce overall vehicle processing time by combining steps
- **Risks**
  - Size of support structures may consume floor space savings
  - Pits and decks represent safety hazards and create maintenance/repair challenges

Figure A-1: One-pager template for evaluating sealing cell concepts



Metric	Solution A	Solution B	Solution C
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Lean criteria 4	◐ Equivalent	◐ Equivalent	◐ Equivalent
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Lean criteria 6	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 7	◐ Equivalent	◐ Equivalent	◐ Equivalent
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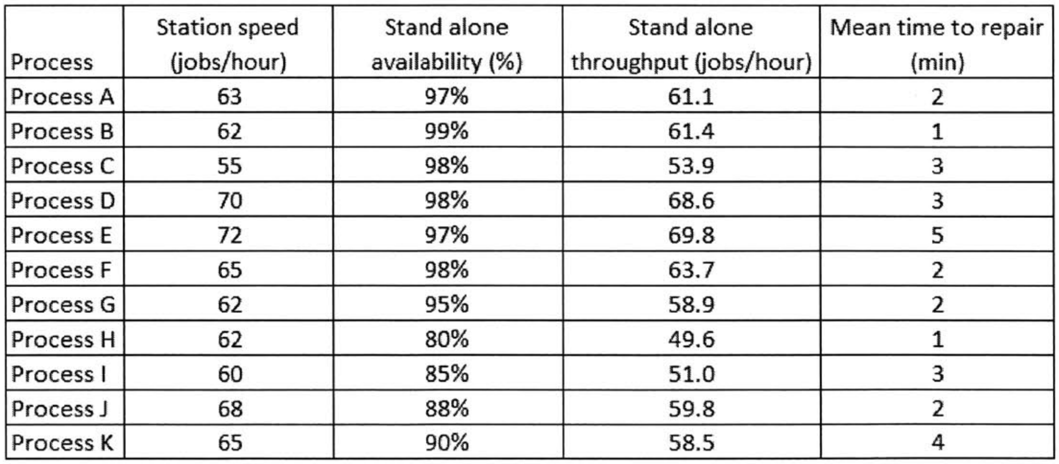
Lean criteria 18	◐ Equivalent	◐ Equivalent	◐ Equivalent
Lean criteria 19	◔ Acceptable	◔ Acceptable	◔ Acceptable
Lean criteria 20	◔ Acceptable	◔ Acceptable	◐ Equivalent
Overall	6	8	9

Figure A-2: Sample of score card used to assess solutions against baseline using lean design criteria



Process	Station speed (jobs/hour)	Stand alone availability (%)	Stand alone throughput (jobs/hour)	Mean time to repair (min)
Process A	63	97%	61.1	2
Process B	62	99%	61.4	1
Process C	55	98%	53.9	3
Process D	70	98%	68.6	3
Process E	72	97%	69.8	5
Process F	65	98%	63.7	2
Process G	62	95%	58.9	2
Process H	62	80%	49.6	1
Process I	60	85%	51.0	3
Process J	68	88%	59.8	2
Process K	65	90%	58.5	4

Figure A-3: Sample of process data collected in order to complete simulation

Appendix B

Layouts from solution development phase

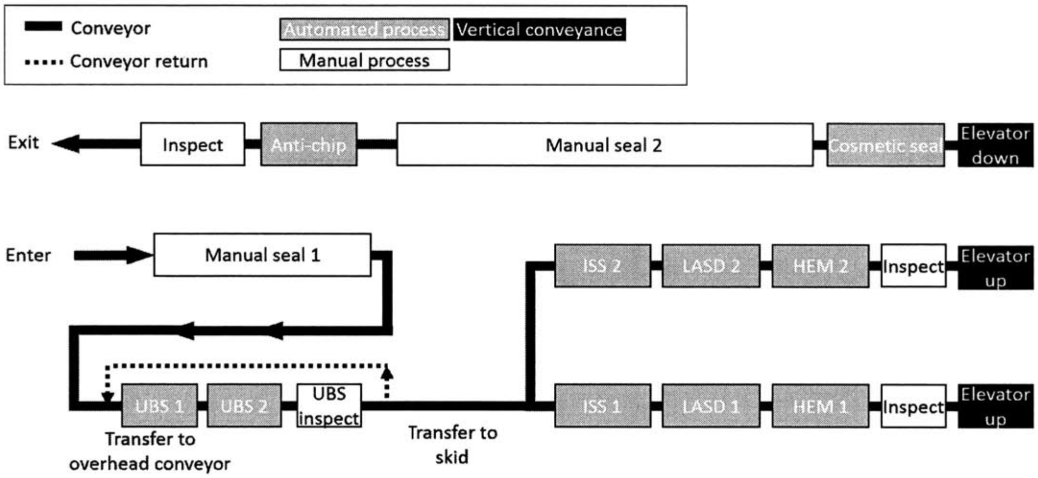


Figure B-1: Layout for baseline facility

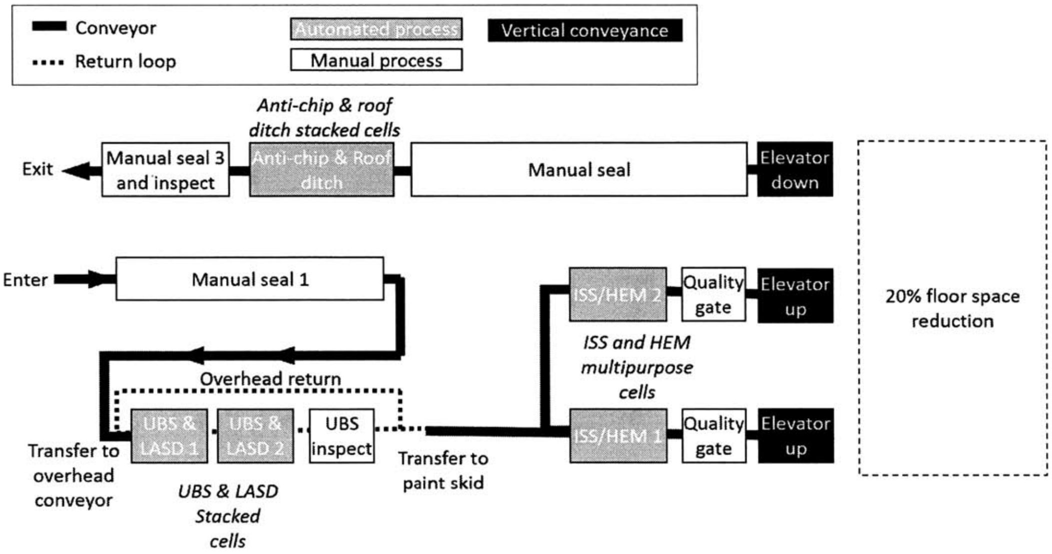


Figure B-2: Layout for solution using stacked cells and multipurpose tooling

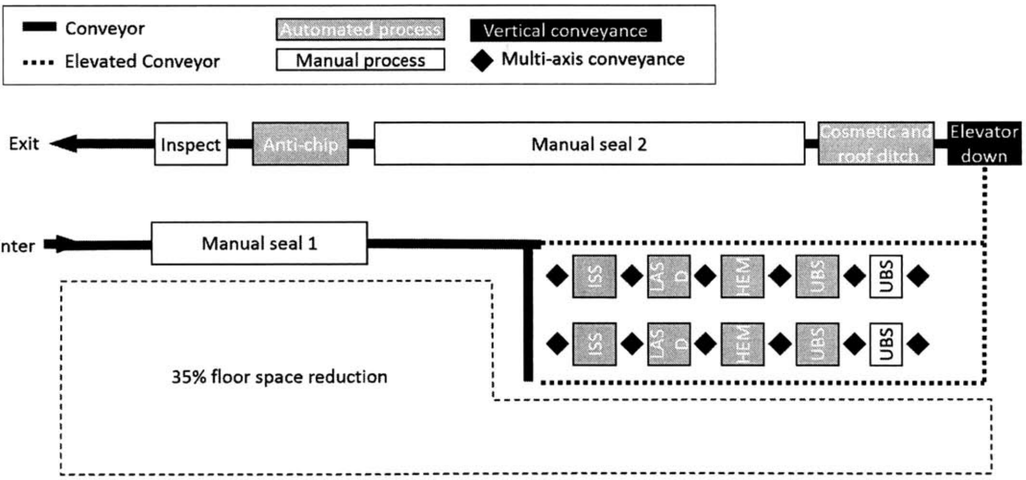


Figure B-3: Layout for solution using multiple fixed multiaxis conveyors

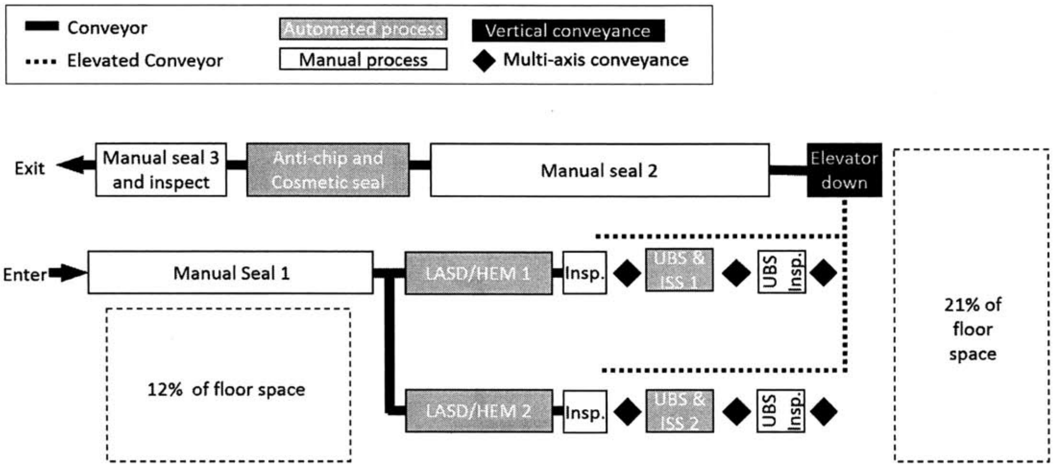


Figure B-4: Layout for solution using stacked cells, compressed cells and multiaxis conveyors

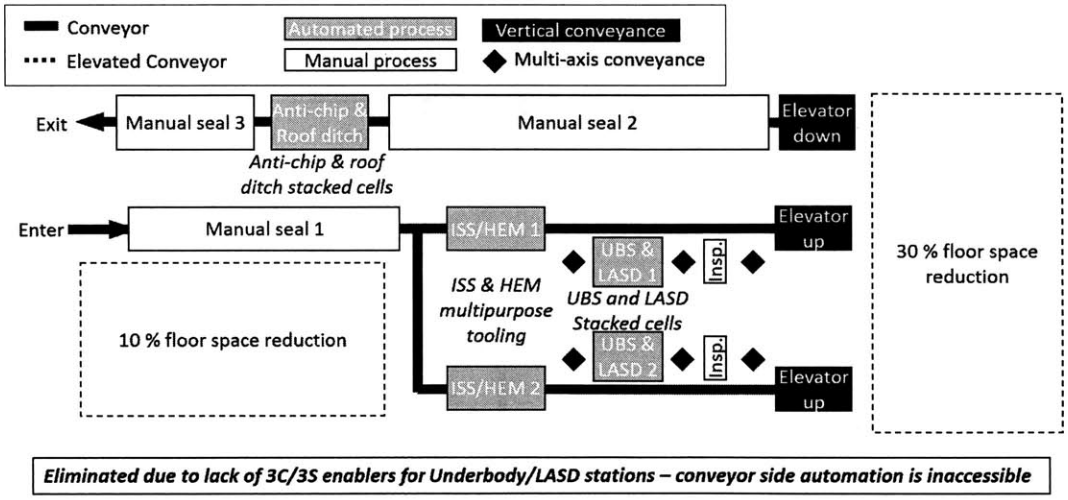


Figure B-5: Layout for solution using multipurpose tooling, multiaxis conveyance and stacked cells

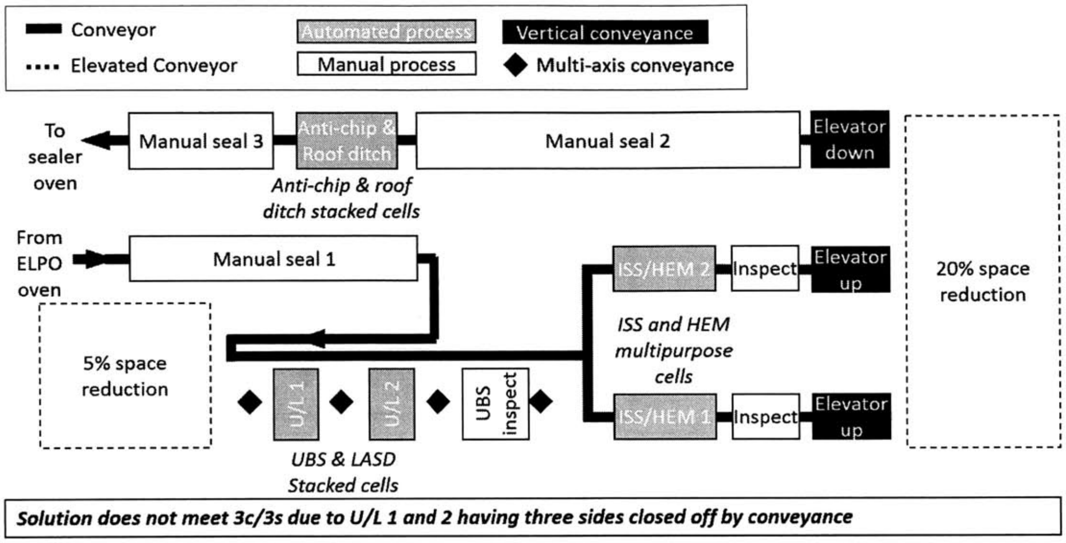


Figure B-6: Layout iteration for solution using multipurpose tooling, multiaxis conveyance and stacked cells

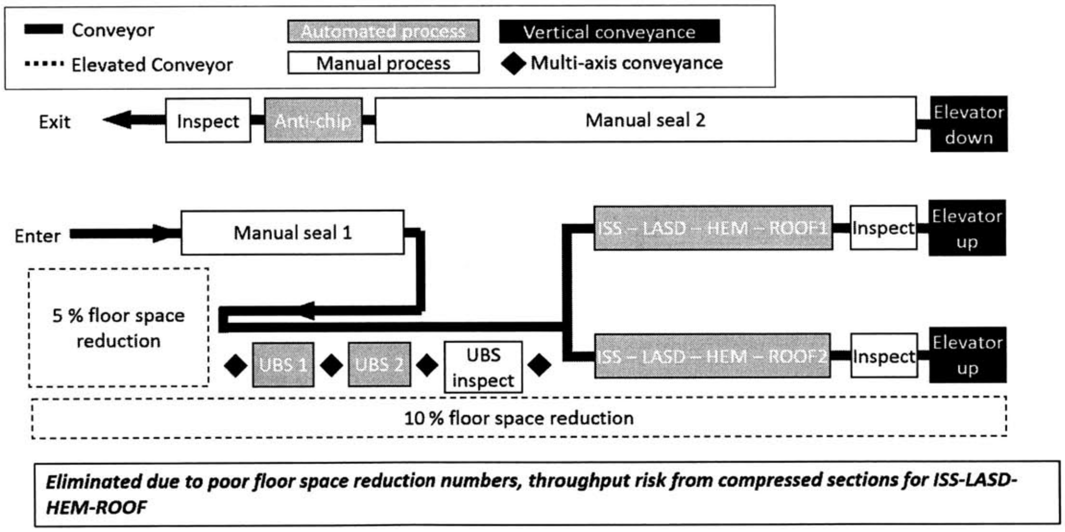


Figure B-7: Layout for solution using multiaxis conveyance and compressed cells

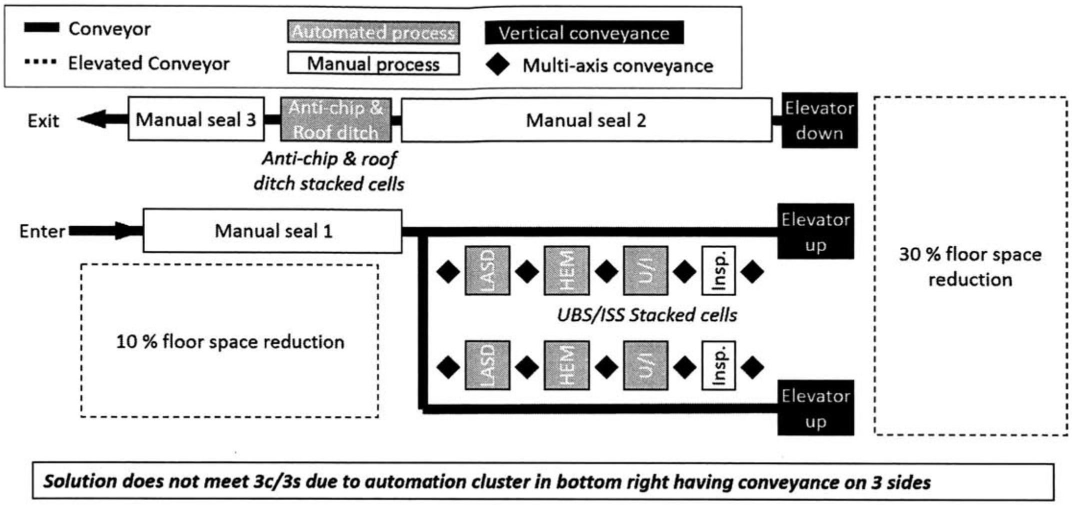


Figure B-8: Layout for solution using multiaxis conveyance and stacked cells

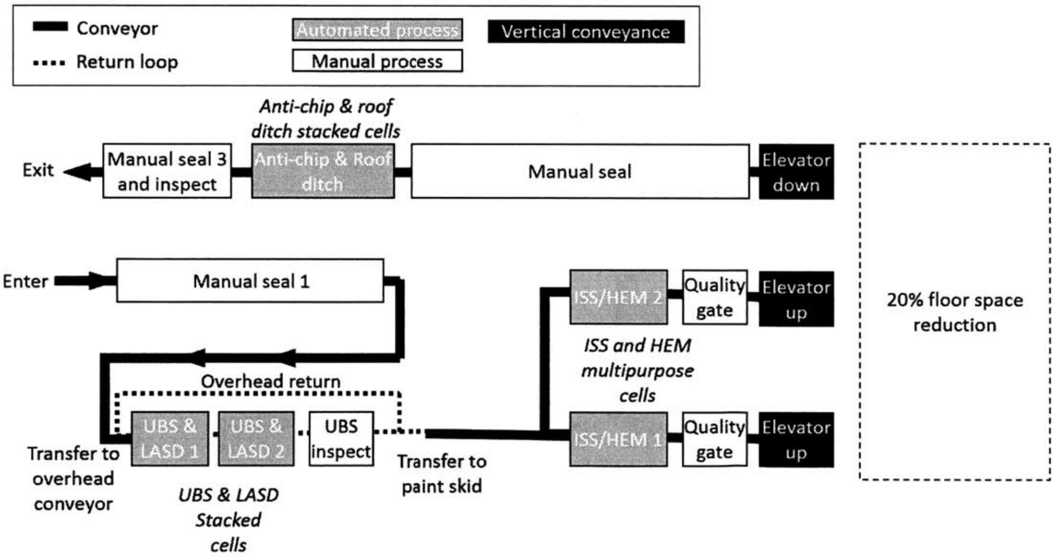


Figure B-9: Layout for solution using stacked cells and multipurpose tooling

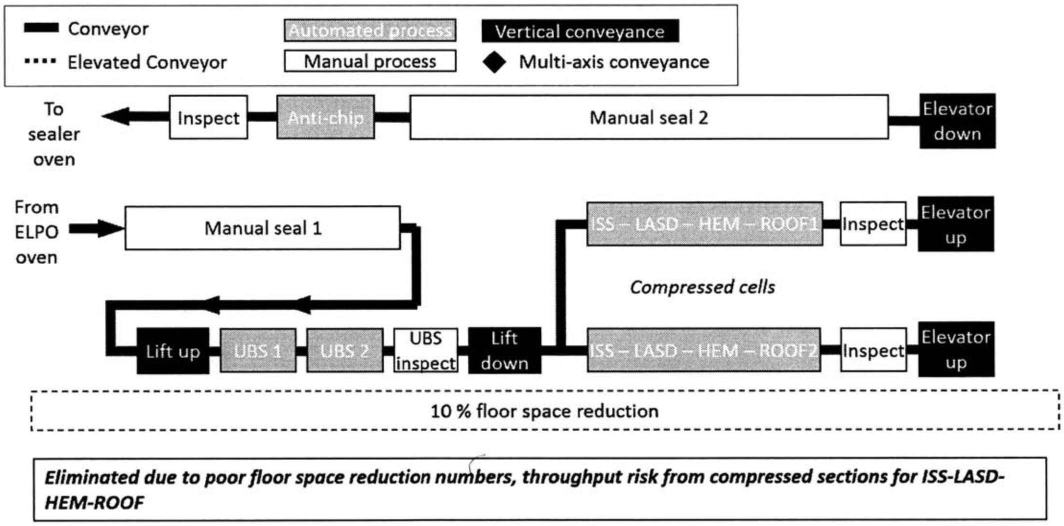


Figure B-10: Layout for solution using UBS lift and compressed cell concepts

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