Cold Chain Management Optimization for COVID-19 Vaccine Distribution

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ABSTRACT

In the wake of the COVID-19 pandemic, biotech companies faced an unprecedented challenge to develop vaccines within a very short time. The revolutionary nature of vaccines has expedited their development and deployment, but their association with ultra-cold storage and transportation poses challenges for equitable distribution. As the world approaches normalcy, there is a shift in demand from multi-dose vials to single-dose vials and pre-filled syringes. This capstone project aims to develop a robust and effective method for selecting cold-chain packaging materials for the biotechnology company's post-pandemic packaging strategy while being in accord with the cold chain requirements. To achieve this, the project identifies and analyzes critical factors impacting thermo packaging solutions The study found that packaging options based on the mode, duration, and demand of transportation make it easier to visualize the network into manageable chunks and select the appropriate packaging for each cluster. The report aims to build a model that analyzes cost, risk, and environmental factors for global strategic cold chain packaging programming. The methodology employed and model were developed for vaccine manufacturers but can serve other industries and packaging programs. Through the utilization of the implemented methodology and selected model, organizations can assess different packaging options and make well-informed and strategic decisions regarding their packaging program, ultimately enhancing their product delivery process.

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## 1. INTRODUCTION

Within weeks of the first reported cases, international biotech companies were formulating to the Wuhan strain, building supply chains, and deprioritizing other products to develop a vaccine to combat COVID-19 on a global level. Unprecedented collaboration between vaccine regulators and manufacturers accelerated the approval of COVID-19 vaccines, highlighting a unique global mission and a constructive partnership that allowed for efficient yet thorough evaluation processes. However, there was pushback from some segments of the public on getting the vaccination. This pushback was driven by the concerns over the speed of vaccine development and due to limited data to fully understand the impact of the products on humans. Within a year, leading pharmaceutical companies were able to produce a vaccine with adequate immune response. The effect of these vaccines protected humans from serious or fatal effects from getting COVID-19 and was approved for usage by government agencies across the globe. One of the advantages of this vaccine development technology is that it requires a less stringent cold chain, making it easier to distribute and store (CDC-2, 2022). The new vaccines brought to market bestowed varying level of logistics and cold chain management needs determined by the temperature ranges they required to ensure their effectiveness.

To mitigate vaccine loss and waste, biotechnology companies have been working closely with packaging manufacturers to develop newer and better packaging configurations. Initially, vaccine manufacturers created mass-vaccine presentations for high-volume injections at sites to meet the pandemic needs. However, to better align with changing public needs, and to cost-effectively deliver doses, the presentations are evolving to include single dose vials as well as prefilled syringe options. These changes in presentations have enormous impacts on logistics strategy, planning, cost, and optimization. By shifting from mass-vaccine presentations to single dose vials and prefilled syringes, vaccine producers aim to meet the diverse needs of the public while ensuring efficient distribution and minimizing waste. The vaccines are

manufactured in production facilities, and in response to these developments, each vial or syringe will be packed individually after manufacturing and then shipped to the designated destinations. The vaccines are then shipped to approved destination countries through authorized shippers. The transportation to each destination is referred to as a lane. Once the vaccines arrive, they are either delivered directly to the government facilities of the respective countries or to regional distribution centers, depending on the specific arrangements in place. The current packaging configuration allows for efficient transport, with a specific number of vaccines accommodated on a pallet. However, with the shift towards Single Dose Vials (SDV) and Pre-Filled Syringes (PFS) due to the product demand lifecycle, that is pandemic to post-pandemic conditions. In post-pandemic scenario, each dose would be individually packaged, thereby dramatically impacting the quantity of doses that can be carried on a pallet. This shift requires adjustments in the cold-chain packaging for SDVs and PFS to ensure optimal transport and distribution.

## 1.1 PROBLEM STATEMENT AND RESEARCH QUESTIONS

The COVID-19 vaccine is being distributed across the world by various organizations in bulk packages (pallets) through the pandemic. Vaccine distribution entails multiple number of doses being packed in a bottle called a vial, and often referred as the primary packaging. Cartons consist of several vials known as the secondary packaging. Several cartons are packed into a case and finally several cases make up a full pallet. The shipper or case is the outermost layer. Pallets of COVID-19 vaccines are transported through various modes such as air, rail, and road to customers across the globe. COVID-19 vaccines were predominantly transported by road and air due to the urgent demand. Certain vaccines with enhanced shelf life, could be suitable for other modes of shipping, although, air and road transportation were the primary means for delivering COVID-19 vaccines. During the pandemic vaccines were delivered in bulk to

government agencies who employed their own final mile solutions to reach the target population. The post-pandemic distribution model involves a return to typical vaccine delivery structures. This includes changes in primary product packaging as well as delivering vaccines to the customers in market through distributors, wholesalers, clinics, pharmacies, hospitals, and general practitioners.

A major differentiating factor between the pandemic and the post-pandemic era of the COVID-19 vaccine distribution strategy is the type of packaging: Multi Dose Vials (MDV), Single Dose Vials (SDV), or Pre-filled Syringes (PFS). Moving from an MDV model to a SDV or PFS model will transform vaccination supply chains for network strategy plans, capacities, and the quantity and type of packaging used (primary, secondary, and tertiary). An immediate and dramatic outcome relates to packaging, as SDVs would require a separate primary packaging for each dose causing the number of doses per pallet decreasing more than ten-fold. Moreover, packaging requirements would increase exponentially from pandemic to post-pandemic model, making the selection of proper cold-chain package very important with respect to factors like cost, risk, and environmental. In that context, the questions to be answered in this capstone research include:

- What are the critical factors impacting selection of tertiary packaging for post-pandemic vaccine distribution?
- Which tertiary packaging is best for a post-pandemic packaging?
- What is the impact this analysis can have on packaging programs?

## 1.2 PROJECT GOALS AND EXPECTED OUTCOMES

The goal of this project is to have a robust thermo packaging selection mechanism. This would be achieved by determining key selection criteria and by providing methods for incorporating criteria with a changing supply chain, and to offer recommendations based on current cold

chain packaging market offerings. For the biotech companies, it is crucial to address important strategic themes such as risk, environment, and costs. These themes directly impact the company's operations, sustainability, and profitability. Risk management is crucial for companies to ensure the smooth functioning of operations and mitigate potential disruptions. This includes assessing and addressing various risks that could impact the supply chain, product quality, and timely delivery of vaccines. Factors such as vendor lead times and ease of vendor onboarding fall under this theme as they directly impact the company's ability to maintain a reliable supply chain. In today's environmentally conscious world, it is vital for companies, including vaccine manufacturers, to consider their ecological footprint. The carbon footprint factor highlights the environmental impact associated with vaccine packaging and transportation. By adopting sustainable practices and choosing eco-friendly materials, the company can reduce its carbon footprint and contribute to environmental conservation. Cost optimization is a critical aspect of any business, and the vaccine company is no exception. The cost of material factor directly relates to the company's financial performance and profitability. By carefully evaluating different packaging material options, the company can strike a balance between cost and quality. We hypothesize that a data-driven set of prioritization criteria would be the best way to objectively identify choice of thermo packaging. To identify the most appropriate method for selecting thermo packaging for vaccine distribution, we will review the literature regarding factors affecting packaging material in transportation and implementation practices.

The research provides a robust, data-driven process for selecting a thermo package solution for multi-dose and single-dose vial presentations that incorporate the following factors:

a) Risk factors: Vendor lead times, Ease of vendor onboarding, Validation time

b) Environmental factor: Carbon footprint

c) Cost Factors: Number of doses per package, Cost of packaging

To identify the most appropriate thermo packaging options, our project plan included the following steps. First, we reviewed industry wide literature to understand the vaccine manufacturing landscape as well as the specific attributes to appreciate for pandemic conditions. In this step we studied various processes which can be used in our capstone project to select the most appropriate cold-chain packaging. Second, we develop a methodology based on findings from the literature review. Third, we present the results obtained after executing various steps described in the Methodology section. We conclude with tangible results for vaccine manufacturers and thermo packaging recommendations from the model developed.

## 2. STATE OF THE ART

This chapter discusses the literature on vaccine supply chains and methods for making decisions related to cold chain management practices in support of efficient and effective supply chains. The research led to insights which enabled the development of methodology and a model for robust thermo-package selection.

### 2.1 VACCINE SUPPLY CHAINS

The focus of many vaccine companies across the globe had primarily been on developing new vaccines, measuring their efficacy, and finally launching them to the public (Lee & Haidari, 2017). But in the past few years there has been a shift in the way companies look at the overall picture of vaccine development to vaccine delivery. For example, during 2006, when the initial packaging of the certain vaccinations was larger than routine vaccines, it created a bottleneck while it was being transported to Latin America because the maritime container size was larger in the US compared to the rest of the world. This bottleneck disrupted the flow of the vaccines and the pharmaceutical companies creating this vaccine had to redesign the packages (Oliveira et al., 2014). Similarly, due to supply chain issues, to include last mile cold chain challenges, the World Health Organization has not been able to achieve its goals on controlling, eliminating or eradicating diseases such as polio and measles (WHO, 2014). These are a few of the many incidents that have made pharmaceutical companies include a focus on the planning of vaccine supply chains in accord with the development of the vaccines.

During the COVID global pandemic, the world quickly gained appreciation for global supply chain planning, and cold chain management. The mRNA products specifically highlighted this specialty with their challenging -60C to -80C storage and transport requirements. The cold chain industry and their products were at the forefront of supply chain planning for vaccine manufacturers. Keeping supply chains, cold chain, and packaging as the key focus areas and

working on them well in advance of vaccine market availability, pharmaceutical companies were able to develop more effective vaccine delivery programs (Fahrni et al., 2022).

### 2.1.1 Cold Chain Management & Transportation of COVID-19 Vaccines

The COVID-19 vaccine's immunogenicity and effectiveness depend on three critical factors after it has been manufactured:

1. Shelf-life of the product
2. Time Out of Refrigeration (ToR) of product before use
3. Degree of the ToR

By keeping the above factors in the forefront, product loss can be avoided from temperature excursions impacting the effectiveness of the product, leading to lower vaccine waste, and reducing loss of potency or effectiveness (Holm & Poland, 2021). To safeguard products in cold chain, an extensive infrastructure is required. Cold chains are managed effectively by monitoring the temperature of the vaccine throughout the supply chain and taking precautions and corrective actions to minimize the occurrence and impact of temperature excursions. COVID-19 vaccines during the 'pandemic' distribution model were transported from manufacturing sites to government facilities in temperature-controlled environments. The biotechnology industry has been implementing this in two ways for bulk shipments of the vaccines, though these methods are independent of type of packaging, rather these are two separate cold chains. The first method is shipping the vaccines in an active container which is run by electricity to keep the temperature at the required level. If the temperature falls below the required range, batteries are replenished to maintain the temperature (Holm & Poland, 2021).

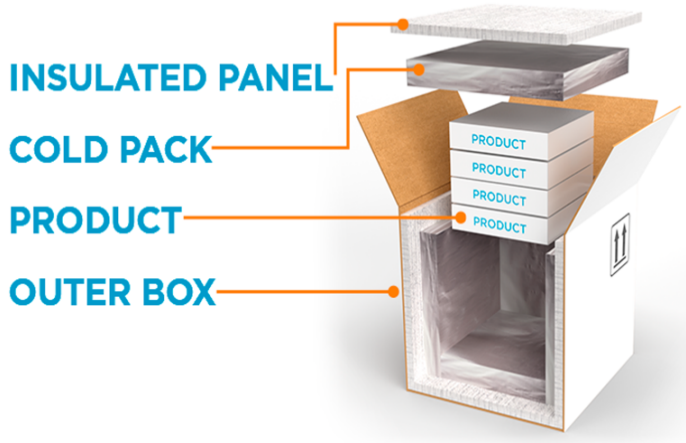
The second method is by using passive cooling technology. The passive container is manufactured with insulation material and a cooling agent. With the combination of the insulation and the coolant, the temperature of the container can be maintained at the desired

temperature for an amount of time which varies depending on the external temperature and humidity. Both methods are used to move products in various packaging type. Active systems present lower risks to products due to the continuous supply of energy that enables temperature control, making it theoretically possible to maintain desired temperatures indefinitely. On the other hand, passive options pose higher risks as they have expiration dates and less robust packaging. In practical terms, events like customs delays or forklift incidents can compromise the integrity of passive cold chains, whereas such concerns are comparatively less significant for active systems. However, active systems may face challenges in the final mile of delivery in developing countries, requiring considerable investment in terms of cost and infrastructure for their maintenance, return, and programming (Catizone, 2013). Understanding the cost/benefit relationship between active cooling and passive cooling container types is critical to our research. Active containers are considerably more expensive than passive containers, have less associated packaging waste, and low risk of product loss due to excursions. However, active solutions have a high energy requirement for maintaining temperature and circulation within the containers as well as significant energy and resource requirements for manufacturing and end-of-life processes. These benefits can be compelling when it comes to overarching corporate social responsibilities like safeguarding environment and other allied goals. In general requirement like in this case, passive containers are sufficient. It is noteworthy that while passive containers may have slightly higher product losses, the industry has transitioned to their use due to the performance and reliability they offer. The infrequent occurrence of losses with passive containers renders active containers cost prohibitive. This factor is appreciated throughout the industry. It is also worth noting that in some cases, customers may demand the use of active containers for increased security and peace of mind. However, the decision to use active or passive containers ultimately depends on the specific requirements, cost considerations, and risk assessments of each situation.

2.1.2 Packaging of Vaccines though Passive Container

The first step in the supply chain of the vaccine after its production is the packaging. Vaccines are packed into vials or syringes, which we see used by health practitioners to administer vaccines to patients throughout the world. These vials or syringes are known as the primary packaging of the vaccine. The initial packaging of the vaccines consists of primary packages, containing different quantities of doses, which are then placed within cartons referred to as the secondary package. These secondary packages are further enclosed in shippers or cases, known as the tertiary package. The tertiary package is supported by cold chain management solutions, which can involve various methods such as placing individual cases within a thermal package or arranging a pallet of cases inside a larger thermal package. Additionally, refrigerated trucks can be utilized to transport pallets of vaccines, serving as a large-scale thermal packaging solution (Ramakanth et al., 2021).

**Figure 1: Cold Chain Packaging**




From *Ramakanth et al., 2021*

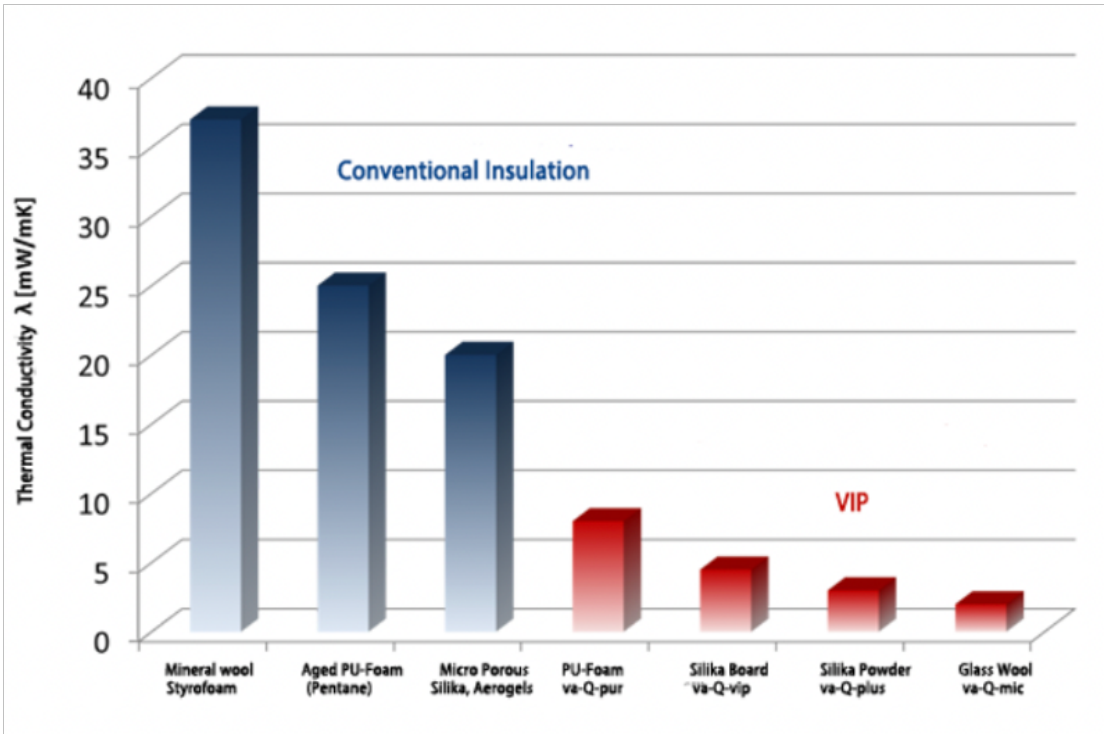
**Figure 2: Packaging and supply chain of COVID -19 Vaccines**


From *Ramakanth et al., 2021*

2.1.3 Insulation material for cold-chain packaging of COVID-19 Vaccines

Various types of insulation materials are used to manage the temperature conditions at the desired levels to safeguard products. There are several insulation materials available commercially, but these can be divided into two categories: conventional insulation and vacuum insulated packaging. The vacuum insulated packaging (VIP) has lower thermal conductivity than the conventional type such as wool, styrofoam, polyurethane, and micro porous silica (shown in Figure 3). Hence, passive containers having VIP based insulation keep the vaccine cooler for a longer period than the conventional. The weight and the thickness of the VIP is the least among all types of insulations, thereby helping reduce transportation cost and carbon footprint.

**Figure 3: Thermal conductivity of insulating materials**




From *Ramakanth et al., 2021*

VIPs have flat panels for optimized temperature insulation. These panels offer heat insulation at minimum thickness. VIP has pressure-resistant core material consisting of a compressed plate of micro-porous powder, silica board, PU foam, or glass wool. The core of the VIP packaging is evacuated (pumped void of air) and sealed in a high-barrier film. Hence, it is protected against air and water intrusion. This allows it to provide higher thermal insulation and offer a service life of up to 50 years (WHO, 2014).

Vacuum insulated panels (VIPs) are specifically engineered with flat panels to maximize temperature insulation capabilities. These panels offer effective heat insulation while keeping thickness to a minimum. The core material of VIPs commonly consists of a pressure-resistant substance, such as compressed micro-porous powder, silica board, PU foam, or glass wool. The core is evacuated by removing all air from it and subsequently sealed within a high-barrier film. This vacuum sealing provides protection against air and water infiltration, leading to

enhanced thermal insulation properties. Notably, VIP packaging is renowned for its extended service life, which can reach up to 50 years. In terms of availability, VIPs are commercially available for use in the transportation of temperature-sensitive products, including vaccines. However, they are generally more expensive compared to other materials. Effectiveness-wise, VIPs offer excellent temperature insulation capabilities, reducing the risk of temperature excursions and helping to maintain the desired temperature range for the vaccines during transportation. The vacuum sealing and high-quality insulation of VIPs contribute to their effectiveness in preserving the integrity of the vaccines. When it comes to cost, active containers, including VIPs, tend to be more expensive than other materials. The use of advanced materials, vacuum sealing technology, and long service life contribute to the higher cost. This cost factor should be considered when considering the overall logistics and budgetary requirements. Regarding environmental impact, the long service life of VIPs can be seen as a positive attribute, as it reduces the need for frequent replacements and minimizes waste generation. Additionally, the energy-efficient insulation properties of VIPs can contribute to reducing energy consumption during transportation, which aligns with sustainability goals.

2.1.4 Coolant for cold-chain packaging of COVID -19 Vaccine

Coolant is pre-cured to the required temperature and depending on its latent energy, it keeps the vaccine at the required temperature for a certain duration of time. Various type of coolants available for passive containers include:

1. Frozen icepacks: Ice packs are commonly used as a cooling method for vaccine transportation and storage. These packs consist of a mixture of ice that helps maintain a low temperature. Ice packs are typically pre-frozen and then placed alongside the vaccines to provide cooling during transit or storage. Ice packs offer several advantages in vaccine cold chain logistics. They provide effective cooling and can maintain low temperatures for extended periods, helping to preserve the integrity and potency of vaccines. They are also

relatively easy to handle and activate by simply freezing them prior to use. Ice packs are widely available and cost-effective, making them a practical choice for many vaccine distribution scenarios. Ice packs can present a freezing risk if they come into direct contact with the vaccines, potentially compromising their quality. It is important to use proper insulation, such as placing the vaccines in secondary packaging or using dividers, to prevent direct contact. Additionally, as ice packs melt, there is a possibility of water leakage, which can be managed by ensuring proper packaging and handling procedures.

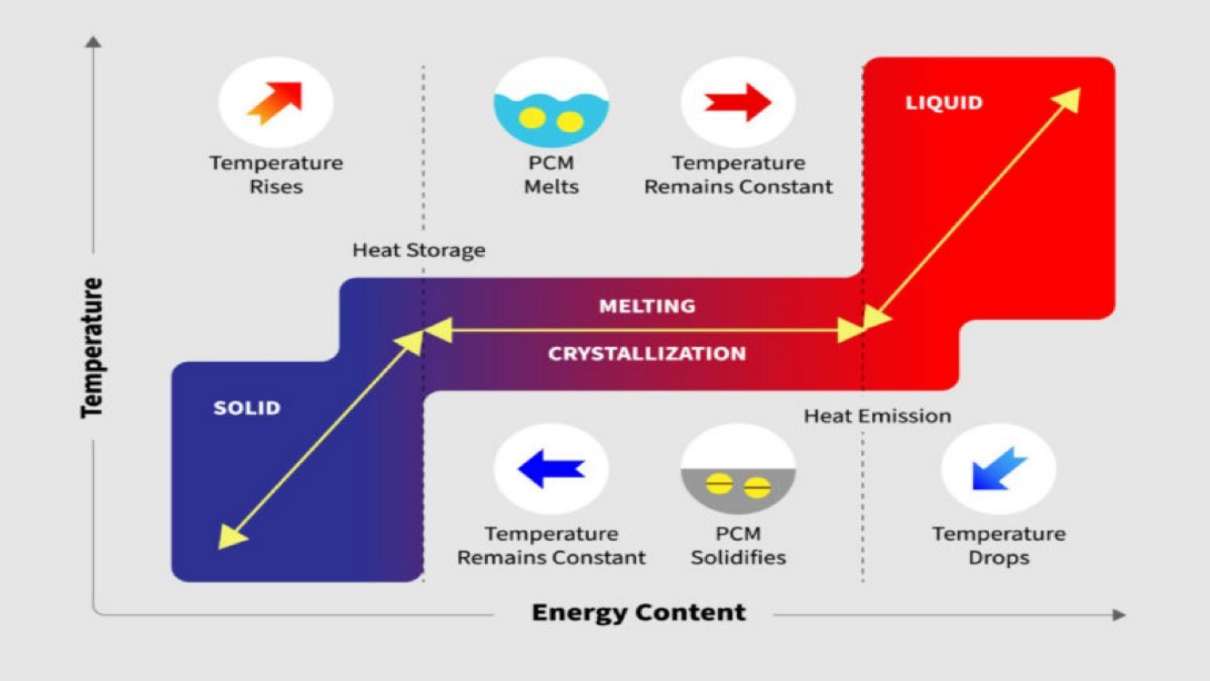
2. Dry Ice: Dry ice, or solid carbon dioxide, is another cooling method used in vaccine transportation and storage. It is extremely cold, with temperatures as low as -78.5°C (-109.3°F). Dry ice is typically placed in insulated containers or packages alongside the vaccines to maintain the required temperature range. Dry ice offers several advantages as a cooling solution. It provides very low temperatures, which can effectively preserve vaccines that require extremely cold storage conditions. It also has a longer duration of cooling compared to traditional ice packs, making it suitable for longer transportation periods. Dry ice sublimates (turns directly from solid to gas) without leaving any residue, eliminating the risk of water leakage or damage to the vaccines. However, there are some considerations and precautions when using dry ice. It is essential to handle dry ice with proper protective gear, as direct contact with skin can cause severe burns. Ventilation is crucial to prevent the buildup of carbon dioxide gas, as excessive concentrations can lead to asphyxiation. Additionally, the use of dry ice requires compliance with regulatory guidelines due to its hazardous nature.
3. Cool water-based gel packs: Cool water-based gel packs are widely used in the transportation and storage of vaccines to ensure temperature control. These gel packs contain liquid water that is initially maintained at temperatures between +2°C and +8°C. They serve as an alternative to traditional ice packs, eliminating the risk of freezing while

still providing effective cooling. These gel packs find application in various use-cases. Firstly, they are commonly employed in vaccine transportation within the cold chain logistics. By maintaining the required temperature range, they safeguard the integrity and efficacy of the vaccines during transit. Additionally, cool water-based gel packs are used in refrigerated storage units or coolers to regulate and sustain the desired temperature for vaccines. They offer reliable and consistent cooling within the specified temperature range. Moreover, they are easy to handle and use, as they can be activated by immersing them in water and are flexible enough to conform to different packaging configurations. However, there are some limitations to consider. Cool water-based gel packs have a shorter cooling duration compared to ice packs, requiring more frequent replacement or recharging. Additionally, they may not provide the same level of cooling performance as ice packs, especially in extreme temperature conditions or for prolonged storage durations.

4. Phase-change material packs (PCM-packs): These contain phase-change materials that are generally not water based. Fill materials include various types of paraffin wax or vegetable sourced substances. The advantage of PCMs is that they can be designed to change phase at temperatures within the +2°C to +8°C range recommended for vaccine storage and transport. This overcomes the vaccine freezing risk associated with frozen water. PCM-packs have a significantly better cooling performance than water-based gel packs on a weight-for-weight and volume-for-volume basis, though they are also more expensive. Finally, to trigger the freezing process, PCM-packs generally must be frozen in a freezer and then conditioned for up to 24 hours in a refrigerator before use. This two-stage procedure reintroduces the compliance problems associated with conditioning icepacks (WHO, 2015). In terms of availability, PCM-packs are commercially available for use in temperature-sensitive product transportation, including vaccines. They are designed to provide reliable temperature control during transit. Effectiveness-wise, PCM-packs exhibit

significantly better cooling performance compared to water-based gel packs when considering their weight and volume. The ability of phase-change materials to store and release thermal energy during the phase change process helps maintain the desired temperature range for the vaccines. This efficient temperature control contributes to the effectiveness of PCM-packs in preserving the integrity of vaccines during transportation. However, it is important to note that PCM-packs are generally more expensive than water-based gel packs due to the materials used and the manufacturing process. The cost factor should be considered when evaluating the overall logistics and budgetary requirements for vaccine distribution. Regarding environmental impact, the specific impact of PCM-packs depends on the materials used in their construction. Some phase-change materials, such as paraffin wax, can have environmental concerns due to their petroleum-based origins. However, there are also PCM options available that are sourced from vegetable-based substances, which may have a lower environmental impact. It is important to choose PCM-packs made from sustainable and environmentally friendly materials to minimize their overall impact. It is worth noting that PCM-packs require a two-stage procedure for their use. They need to be initially frozen in a freezer and then conditioned for up to 24 hours in a refrigerator before use. Figure 4 below depicts how phase change materials work.

**Figure 4:** Phase change material state change flow




From *Ramakanth et al., 2021*

PCM (Phase Change Material) packs provide an advantageous cooling solution for vaccine transportation and storage. These packs contain materials that can change phase within the recommended temperature range of +2°C to +8°C, eliminating the risk of vaccine freezing. PCM offer superior cooling performance compared to water-based gel packs, effectively preserving vaccine integrity during transit. The thermal energy stored and released during the phase change process contributes to their effectiveness. Opting for PCM-packs made from sustainable, vegetable-based substances can mitigate environmental implications. Despite this conditioning process, PCM-packs ensure reliable temperature control during transit. Their benefits lie in preventing freezing, efficient cooling performance, and maintaining the desired temperature range. In conclusion, PCM offers a compelling solution for vaccine distribution, delivering effective temperature control. Factors such as cost, environmental impact, and the conditioning procedure should be considered when assessing their suitability for specific distribution scenarios.

## 2.2 METHODS TO SUPPORT DECISION MAKING

This sub-section investigates various methods to support decision making relevant to the research topic at hand. Since the topic deals with selection of a solution based on multiple criteria, we review the literature on multi-attribute decision making and methods for quantification and solving multi-attribute decision making problems.

### 2.2.1 Multiple Criteria Decision Making

Multiple Criteria Decision Making (MCDM) is the branch of operations research which entails methods to select the most appropriate decision with multiple criteria. Multiple Criteria Decision Making is further divided into two broad areas of research:

- Multiple Objective Decision Making (MODM)
- Multiple Attribute Decision Making (MADM)

Though MODM and MADM vary based on their applications, a major differentiating factor is that MODM deals with the problems where decision space is continuous whereas MADM would generally be applicable to the problems where decision space is discrete. Moreover, MODM deals with decision spaces that involve continuous variables, allowing for a wide range of values, while MADM is suited for decision spaces that involve discrete options, where choices are limited to specific, distinct alternatives. Understanding the nature of the decision space is crucial in determining the appropriate decision-making technique to apply in each situation. Since our area of research entails discrete decision making, we will have a focus on MADM and in all further writings (Triantaphyllou et al., 1998).

Methods of Multi Attribute Decision Making:

- Weighted Sum Model (WSM): A decision-making method that calculates the overall score of alternatives by assigning weights to criteria and aggregating their respective scores.
- AHP: Analytical Hierarchy Process: A structured decision-making technique that allows for the prioritization and selection of alternatives based on a hierarchy of criteria, using pairwise comparisons and mathematical calculations.

- ELECTERE: Elimination and Choice Translating Reality: A decision-making method that systematically eliminates alternatives based on a set of criteria, leading to the identification of the most desirable option.
- Pugh Convergence: A concept used in engineering design to evaluate and converge on the most suitable design alternative by comparing it to a reference design and assessing its performance against a set of criteria.
- Multi Attribute Value Analysis (MAVA): Multi-Attribute Value Analysis is a decision-making framework that is used to evaluate alternatives based on multiple attributes or criteria. It involves the combination of value functions and criteria weights to provide a useful measure for the attractiveness of different options.

2.2.1.1 Weighted Sum Model (WSM)

The Weighted Sum Model (WSM) is a decision-making method widely used to solve single-dimensional problems. It involves assigning weights to criteria and calculating a weighted sum of scores to determine the best alternative. If there are M alternatives and N criteria then, the best alternative is the one that satisfies the following expression:

$$A^*_{WSM} = \max_i \sum_{j=1}^{N} q_{ij} w_j, \quad for \quad i = 1, 2, 3, ..., M.$$

$A_{WSM}^*$: Weighted Sum Multiplied score of the best alternative.

$N$ : Number of decision criteria

$a_{ij}$ : Actual value of the i-th alternative in terms of the j-th criterion

$W_j$ : Weight of importance of the j-th criterion.

The WSM finds application in various scenarios, including product evaluation, project selection, supplier selection, and performance assessment. Its advantages lie in its simplicity, allowing for easy understanding and quick decision-making with minimal data points. The method offers flexibility by accommodating a wide range of decision criteria and providing

transparency through the explicit incorporation of weights and scores. However, the WSM has drawbacks that need to be considered. It lacks consideration for interdependencies between criteria, making it less accurate when criteria are interrelated or conflicting. The subjectivity in weight assignment introduces biases, and its applicability to multi-dimensional problems is limited. Small variations in weight values can significantly influence the final ranking, raising concerns about result reliability. Therefore, while the WSM is effective for single-dimensional problems, alternative methods may be more suitable for complex, multi-dimensional decision-making scenarios (Triantaphyllou et al., 1998).

2.2.1.2 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is built on breaking down a complex Multi Criteria Decision Making problem into a system of hierarchies. Strength of AHP is that it is scalable and that its hierarchical structure can easily adjust to complex and large problem sets. AHP has drawbacks that it contains too many pairwise comparisons and that it involves manually allocating weights to each of the criterion, which leads to the problem of bias in many cases.

AHP typically builds a structure of an $m \times n$ matrix, where $m$ is the number of alternatives and $n$ is the number of criteria (Triantaphyllou et al., 1998). This matrix is then formed by allotting relative importance or weights to the alternatives in terms of each criterion.

$a_{ij}$ in the $m \times n$ matrix represents the relative value of the alternative $a_i$ when it is considered in terms of criterion $c_j$. Best AHP alternative equation is indicated by the following relationship.

$$A^*_{AHP} = \max_i \sum_{j=1}^{N} q_{ij} w_j, \quad for \quad i = 1, 2, 3, ..., M.$$

2.2.1.3 ELECTERE Method

The ELECTRE (Elimination and Choice Translating Reality) method works on “outranking relations", referring to the comparisons made between alternatives in a decision-making process. In the context of the ELECTRE (Elimination and Choice Translating Reality) method,

outranking relationships are established by conducting pairwise comparisons of alternatives against each other based on different criteria. During the pairwise comparisons, criteria are examined individually, and the decision-maker assesses the degree to which one alternative outranks another. This assessment is based on the relative performance of the alternatives with respect to the given criterion. The decision-maker assigns rankings or scores that reflect their perception of one alternative being better, equal to, or worse than another. By evaluating these pairwise comparisons across all alternatives and criteria, the ELECTRE method aims to determine the overall outranking relationships among the alternatives. This process helps in identifying the alternatives that are superior, inferior, or incomparable to others.

The outranking relationships provide valuable insights into the relative strengths and weaknesses of the alternatives, aiding the decision-maker in making informed choices. It allows for a comprehensive analysis of multiple criteria and their impact on the decision-making process (Triantaphyllou et al., 1998).

2.2.1.4 Pugh Controlled Convergence (PuCC)

Pugh Controlled Convergence (PuCC) is an iterative process that emerged to meet the need for product development teams to engage in iterative design processes for selecting the best concepts. Like the methods, PuCC is represented and processed as an m × n matrix, where columns typically represent different design concepts presented as text labels or diagrams. The rows correspond to selected criteria used for evaluating the concepts or options in the columns. What sets PuCC apart is its requirement for a datum, which is typically an existing design concept or product that stakeholders have sufficient knowledge about (Frey et al., 2009). Steps for performing one iteration of PuCC are as below:

- Create a set of design concepts to be evaluated
- Model a set of opinions held by a group of experts
- Generate the Pugh matrix

- Eliminate concepts based on the Pugh matrix

There are several disadvantages attached to using this method. For instance, the process lacks flexibility once the Pugh matrix is generated and concepts are eliminated, making it challenging to introduce new concepts or make significant changes. Additionally, PuCC utilizes a simplified evaluation method that may oversimplify the complexity of design concepts and potentially overlook important factors. Lastly, the requirement for a datum assumes sufficient common knowledge among stakeholders, which may limit the exploration of truly innovative ideas.

#### 2.2.1.5 Multi-Attribute Value Analysis (MAVA)

Multi-Attribute Value Analysis is a decision-making framework that is used to evaluate alternatives based on multiple attributes or criteria. It involves the combination of value functions and criteria weights to provide a useful measure for the attractiveness of different options. Value functions represent the marginal value of gains in performance for each attribute, while criteria weights represent attribute trade-offs. By combining these two elements, MAVA can provide a quantitative assessment of the different alternatives being considered and identify the most attractive option. MAVA is used in a variety of contexts, including supply chain management, project evaluation, and impact assessment, among others. It is a flexible framework that can be adapted to different decision-making scenarios and can incorporate both quantitative and qualitative data (Slonim, 2019).

MAVA is presented as a framework to quantify the objectives and priorities of experts within the organization at different levels in a supply chain, including both economic and non-economic objectives. In this paper, MAVA is also shown to facilitate project evaluation and impact assessment, which can help in improving engagement efforts and averting resource deployment.

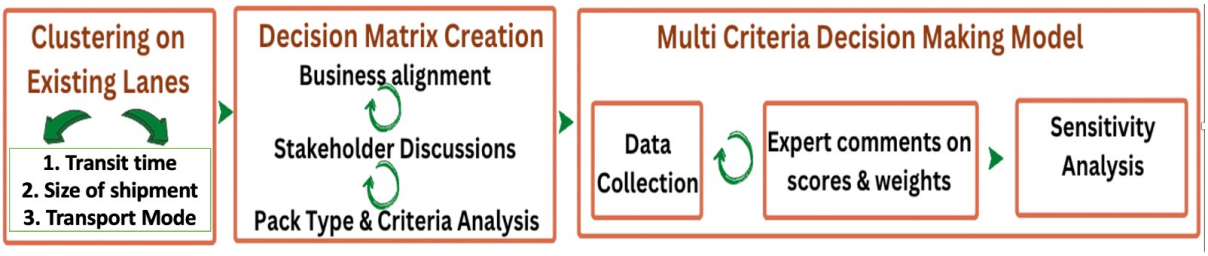
The Multi Attribute Decision Making (MADM) is a method of Multiple Criteria Decision Making (MCDM) that helps to choose the best alternative among multiple options based on various criteria. MADM is applicable to problems where decision space is discrete. There are various methods of MADM, including Weighted Sum Model (WSM), Analytical Hierarchy Process (AHP), ELECTERE, and Pugh Controlled Convergence (PuCC). However, MAVA is a decision-making framework that combines value functions and criteria weights to evaluate alternatives based on multiple attributes or criteria. This method is especially useful where stakeholders play an important role for deciding criteria weights. MAVA can provide a quantitative assessment of different alternatives and identify the most attractive option and can be used in various contexts. Once MAVA is applied, study goes on to conduct straight line sensitivity analysis on the solutions. Straight line sensitivity analysis is a technique used to evaluate the impact of changes in the values of decision criteria or parameters on the overall decision outcome. It involves systematically varying the values of individual criteria while keeping other factors constant and observing the resulting changes in the decision or solution. An important role played by sensitivity analysis in this paper is to understand how robust the solution as weights for criteria is move from 0% to 100%. By systematically varying the weights from 0% to 100%, the study aims to understand how the solution or decision outcome responds to these changes. This analysis helps to determine the robustness of the solution and provides insights into the stability and reliability of the decision-making process. It also allows to assess the degree to which the chosen solution is affected by different weightings and helps in understanding the sensitivity of the overall decision to variations in the criteria weights.

## 3. DATA AND METHODOLOGY

This chapter presents the approach we used to build a model for selecting cold chain thermo packaging, referred to as the concept, by evaluating the various important factors affecting this choice, referred to as the criterion. Vaccine producing biotechnology organizations operate on several routes called lanes, with varied volumes and different transportation modes (i.e., air and road). Therefore, different lanes may have varied requirements and the choice of concepts may change. To develop our methodology, we built on the literature review by evaluating the suitability of the reviewed approaches to the problem being solved here. For developing the decision-making approach, we used Multi Attribute Value Analysis methods like those deployed in Carland et al. (2018) as the research paper solves a different problem in a different context but the research paper provides an excellent base for this research.

The first step towards solving for method to evaluate cold chain package solutions was to cluster all existing lanes into a few similar segments (3.1) and then apply the Multi Attribute Value Analysis process for finalization of the cold-chain packaging for a particular cluster (3.3). Further, sensitivity analysis was conducted to understand the effect of each criterion on results as the relative importance of each criterion changes (3.4). Overview of methodology is shown in Figure 5.

**Figure 5: Overview of Methodology**




### 3.1 DEVELOP CLUSTERS FROM EXISTING LANES

Vaccine distribution supply chains can operate on hundreds and even thousands of transportation lanes across the globe consisting of various countries, modes of transportation,

and durations. Creating clusters from multiple transportation lanes is an essential step in consolidating a large set of lanes into few manageable clusters. Clustering involves grouping transportation lanes that share similar characteristics such as mode of transportation, duration of lanes, and size of shipment.

The first step in creating clusters is to identify the relevant transportation lanes based on the aforementioned factors. Once identified, the transportation lanes are grouped based on the similarities in these factors. The resulting clusters provide a good understanding of the similarities and differences between the transportation lanes. For instance, the clusters can be used to determine the most cost-effective mode of transportation for each cluster or to identify common shipment sizes that can be consolidated for more efficient transportation.

Overall, creating clusters from multiple transportation lanes is a powerful technique that will help vaccine producers streamline their packaging selection decision, improve efficiency, and reduce costs.

## 3.2 CREATION OF FRAMEWORK FOR CONCEPT EVALUATION

Once all existing lanes have been converted into clusters, next step is creation of matrices for these clusters. Matrix can further be divided into two parts: design concepts and criteria for concept evaluation (3.2). Once matrices are developed, swing weights are assigned with the help of industry experts to get the matrices (3.3). Finally, clustered data is subjected to sensitivity analysis enable evaluation of thermo package options on network and representative data set (3.4).

### 3.2.1 Creation of design concepts or alternatives

Selection from the currently available design concepts in the packaging industry is one of the most important inputs to the Multi Attribute Value Analysis as it is not possible for experts to make decisions if decisions are to be made from a huge set of concepts because expert concept

evaluation involves making comparisons on each of the criteria for each concept. Based on our review of literature and discussion with packaging industry companies and experts, we listed design criteria that would be used in our decision-making process (3.2.2). A noteworthy point is that attributes be re-evaluated and changed easily for another industry or problem by understanding the problem at hand and organizational priorities.

3.2.2 Creation of criteria for concept evaluation

Based on our review of literature and discussion with experts, concepts will be evaluated on the following criteria:

a. Container Dimensions (Liters): Container dimension is an important factor for estimating the packing efficiency of a pack type in which it will be transported. Most importantly, container dimensions dictate cost, value of shipment, and shipping constraints - as well as storage. Smaller container dimensions with similar capacity indicate more compact packaging and therefore higher packaging efficiency.
b. Payload Dimensions (Liters): Payload dimension is an important factor for estimating the number of doses that can be carried in a container. This point is amongst the most important for cost and risk. Risk here refers to the number of packages and transporters needed to ship volume of doses.
c. Reusability (Number of uses): Reusability is an important factor from a sustainability point of view. Higher reusability means that a package type is contributing positively towards organization's environmental goals.
d. Cost of packaging ($ each use): Cost of packaging represents the price for usage of packaging for each trip. For single-use type packages, it is the cost of packaging, whereas for reusable type packages, it is the cost of packaging divided by number of uses.
e. Lead times first order (Days): Lead time first order represents the number of days it takes the packaging company to start delivering the packaging for use. First order lead time

typically includes time taken for administrative teams to perform documentation and onboarding.

f. Lead times subsequent order (Days): Lead time subsequent order represents the number of days it takes to receive the packaging after placing the purchase order or requisition. This factor directly impacts packaging availability and risk to shipment delays.

g. Ease of vendor onboarding (1/0): Ease of vendor onboarding is an important factor that is "1" if the vendor is already onboarded and "0" if the vendor is new to the company. Existing vendors' packaging options get an advantage over new vendors because pharmaceutical industry is highly regulated, and it takes considerable time to onboard new vendors.

h. Carbon Footprint (Kg of emissions): Carbon footprint is the amount of carbon emissions caused due to the packaging during each use. For calculating carbon footprint, information on emissions in Kgs during the manufacturing process is provided by the vendor. Carbon footprint is then calculated by dividing emissions by the number of uses of each packaging.

i. Validation Time (Hours): Validation time in the context of pharmaceutical supply chains refers to the time (hours) for which a particular packaging material retains the intended temperature of the payload and is tested and certified by the vendor for a usage cycle. Validation time is often used as a parameter to decide suitability and risk level of a package.

## 3.3 APPLICATION OF MULTI ATTRIBUTE VALUE ANALYSIS PROCESS

To effectively evaluate design concepts, it is crucial to gather quantitative information for each concept against the previously created criteria. A table called a performance matrix is created for each of the clusters. An important feature of our performance matrix is datum. Datum is the concept or packaging selected as the benchmark for a particular lane. Datum is instrumental

for comparing other concepts to the ones currently being used. The performance matrix helps internal stakeholders and decision makers take informed decisions about the relative importance of the concepts on a particular lane.

A Multi Attribute Value Analysis (MAVA) model can be applied using following steps:

1. First, swing weights are used to elicit criteria weights in multi-attribute value analysis. In this method, respondents are asked to consider a decision option that ranks the lowest in all the previously defined attributes. They are then asked to think about their most important swings, ranging from the lowest to the highest level of each attribute, when making the decision on whether to choose the option. The first swing is anchored at 10 and subsequent swings are judged against this first swing. These swing weights are then normalized and aggregated for each cluster. Essentially, swing weights help determine the relative importance of different attributes by considering the range of swings and their impact on decision making.
2. The second step is to convert the performance matrix into a decision matrix. Based on the performance matrix, experts rank every concept on each of the criterion on a scale of -10 to 10, minimum to maximum. The lowest ranked concept on each criterion is the assigned -10 and the highest ranked concept is assigned +10. Then the experts determine exact values in between. This method is chosen because with this approach, if Datum is not better than other options, it also gets penalized, thereby making decision making robust. Further, the scaled numbers in judgement matrix are tuned through inputs from business teams and experts.
3. Once a decision matrix is completed for all concepts across all criteria, final scores are arrived at by combining swing weights with weighted average, with the relative importance of the criteria as decided in the decision matrix. The concept with the highest weighted sum is the choice of packaging on the lane in consideration.

## 3.4 SENSITIVITY ANALYSIS

Sensitivity analysis is a technique used in multi-criteria decision-making models to evaluate how changes in the values of decision criteria affect the final decision outcome (Ishizaka & Nemery, 2013). It is a critical step in the decision-making process, as it helps stakeholders understand the robustness of their decision in the face of uncertainty or changes in the decision criteria. As discussed in section 3.3, in multi-criteria decision making, decision criteria are typically assigned weights that reflect their relative importance. Sensitivity analysis allows decision-makers to assess how changes in the weights of decision criteria affect the final decision outcome. For example, if stakeholders assign a higher weight to a particular criterion, sensitivity analysis can help them understand how sensitive the decision outcome is to changes in that weight. Sensitivity analysis in multi-criteria decision making can be conducted using several methods. We will use one-way sensitivity analysis in our project. One-way sensitivity analysis involves varying one decision criterion while holding all others constant and then observing the resulting changes in the decision outcome. One-way sensitivity analysis is employed in this research to understand the impact of changes in a specific decision criterion on the overall decision outcome. By isolating and varying one criterion at a time while keeping all others constant, this analysis allows us to assess the sensitivity of the decision to changes in that criterion. It helps in identifying the key drivers or influential factors in the decision-making process and provides insights into the relative importance and impact of each criterion. One-way sensitivity analysis also allows to evaluate the robustness of the decision and assess the potential risks and uncertainties associated with variations in a specific criterion. (Hirschberg & Maas, 2007).

# 4. RESULTS AND ANALYSIS

This chapter covers the results obtained through application of steps outlined in the Methodology chapter. We proposed to combine transportation lanes into clusters using method defined in Chapter 3. For illustration, detailed results from one of the clusters are discussed in this chapter. The results for all the other segments can be found in the Appendices.

## 4.1 CLUSTERING

The first step of the clustering process involved separating lanes by their mode of transportation, either air or road. Next, each mode of transportation was further divided based on the average duration of the lanes. For example, according to the 2022 industry shipment data set employed, the air route average duration is 75 hours, which allowed for further clustering of air lanes into those with an average duration less than 75 hours and those with an average duration greater than 75 hours. 75 hours was chosen as there was a clear distinction between shorter and longer routes at 75 hours duration. Similarly, based on 2022 shipping data, road lanes were divided into those with an average duration of less than 48 hours and those with an average duration greater than 48 hours. Based on existing data and a logic like 75 hours lane, 48 hours was chosen. Finally, each of the resulting clusters was divided based on pack sizes, which included full pallets and small parcels (SP).

This clustering process allows for a more detailed analysis of the data set, identifying similarities and differences among lanes based on key features. The resulting clusters can be used to inform operational decisions and optimize the transportation of throughout a network. Table 1 represents the formed clusters from the network lanes mentioned earlier.

**Table 1: Clusters of Lanes Originating from the Central Distribution Center**

| Cluster | Mode | Pack Size | Average Duration |
|---|---|---|---|
| C1 | Air | Full pallet | ≤ 75 hours |
| C2 | Air | Full pallet | > 75 hours |
| C3 | Road | Shipper Package | ≤ 48 hours |
| C4 | Air | Shipper Package | ≤ 75 hours |
| C5 | Air | Shipper Package | > 75 hours |
| C6 | Road | Full pallet | ≤ 48 hours |

### Concept Selection & Sensitivity Analysis

Table 2 is the performance matrix for C2 cluster, which lists various criteria or concepts related to the transportation of vaccines in full pallets where mode of transportation is air and average duration > 75 hours. The table contains information on six different pack types, each with different container and payload dimensions, reusability, cost of packaging, lead times for first and subsequent orders, ease of vendor onboarding, carbon footprint, and validation time. The swing weight column indicates the relative importance or weight of each criterion in the decision-making process assigned by industry experts. As discussed in methodology, swing weights in performance matrix are scaled from 0 to 100. For example, a higher swing weight for container dimensions means that this criterion is relatively more important than other criteria in the decision making.

**Table 2: C2 Performance Matrix**

| Criteria/Concepts | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type1 (Datum) | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| **No of doses per pallet** | 17214 | 21558 | 19122 | 1800 | 19830 | 19122 | 100 |
| **Reusability (times)** | 0 | rental | 30 | 0 | 30 | 30 | 0 |
| **Cost of packaging (each time)** | 1800 | 1700 | 1040 | 1305 | 1990 | 2340 | 95 |
| **Lead times first order(days)** | 15 | 15 | 21 | 15 | 21 | 21 | 0 |
| **Lead times subsequent order(days)** | 7 | 7 | 15 | 7 | 15 | 15 | 0 |
| **Ease of vendor onboarding (1/0)** | 1 | 1 | 0 | 1 | 0 | 0 | 75 |
| **Carbon Footprint (Kgs)** | 215 | 10 | 10 | 215 | 10 | 10 | 20 |
| **Validation Time(hours)** | 120 | 120 | 120 | 96 | 130 | 140 | 0 |

Table 3 is the decision matrix for C2 cluster. Here, swing weights from performance matrix are scaled on percentage importance. Converting raw scores from performance matrix to judgement matrix is important as that would help in weighing each of the criteria based on swing weights.

Based on the judgement matrix (Table 3), Pack Type 3 has the highest score with a total score of 5.3 followed by Pack Type 2 with a score of 4.6. Pack Type 3 outperforms the other pack types in Number of doses per pallet, lead times (first order and subsequent order) and Ease of vendor onboarding. Pack Type 2, on the other hand, performs well in Carbon footprint, Ease of vendor onboarding and lead times (first order and subsequent order).

**Table 3: C2 Decision Matrix**

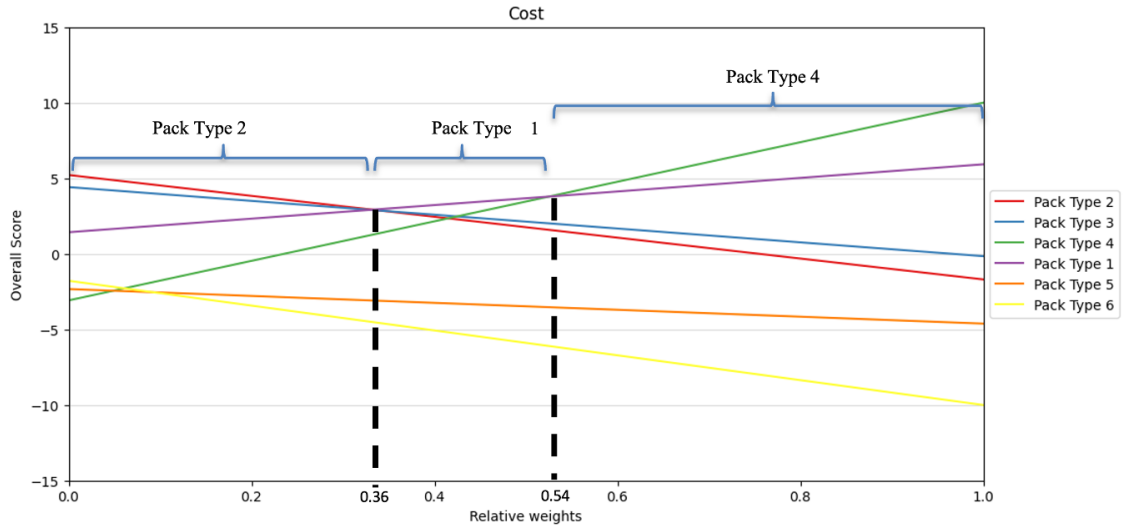
| Criteria/Concepts | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 1 (DATUM) | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| No of doses per pallet | 6 | 10 | 8 | -10 | 8 | 8 | 34% |
| Reusability (times) | -10 | 0 | 10 | -10 | 10 | 10 | 0% |
| Cost of packaging (each time) | -2 | 0 | 10 | 6 | -5 | -10 | 33% |
| Lead times first order (days) | 10 | 10 | -10 | 10 | -10 | -10 | 0% |
| Lead times subsequent order(days) | 10 | 10 | -10 | 10 | -10 | -10 | 0% |
| Ease of vendor onboarding (1/0) | 10 | 10 | -10 | 10 | -10 | -10 | 26% |
| Carbon Footprint (Kgs) | 10 | -10 | -10 | 10 | -10 | -10 | 7% |
| Validation Time (hours) | 1 | 1 | 1 | -10 | 5 | 10 | 0% |
| Final Scores | 4.6 | **5.3** | 2.6 | 1.8 | -1.9 | -3.9 | |

***Sensitivity Analysis***

A sensitivity analysis of the weights shows that these results are robust to variations of significance of each criterion.

The sensitivity analysis in Figure 6 below shows the overall value of different pack types or options based on the weight of criterion-cost of packaging. Each color line represents the overall score of a pack type with the relative weight of cost of packaging ranging from 0 to 1. The findings revealed that as the weight for cost of packaging increased from 0 to 0.36, the preferred choice was Pack Type 2. As the weight increased further to 0.54, the preferred choice became Pack Type 1. Finally, after 0.54 weight for cost of packaging, the choice consistently remained Pack Type 4.

**Figure 6: C2 Cluster Sensitivity Analysis – Cost of Packaging**




The Sensitivity Analysis in Figure 7 shows the overall value of different pack types or options based on the weight of criterion-Number of doses. Each color line represents the overall score of a pack type with the relative weight of number of doses ranging from 0 to 1. The findings revealed that as the weight for cost of packaging increased from 0 to 0.22, the preferred choice was Pack Type 2. As the weight increased further to 0.22, the preferred choice became Pack Type 3 and the choice consistently remained Pack Type 4 thereafter.

**Figure 7: C2 Cluster Sensitivity Analysis – Number of Doses**

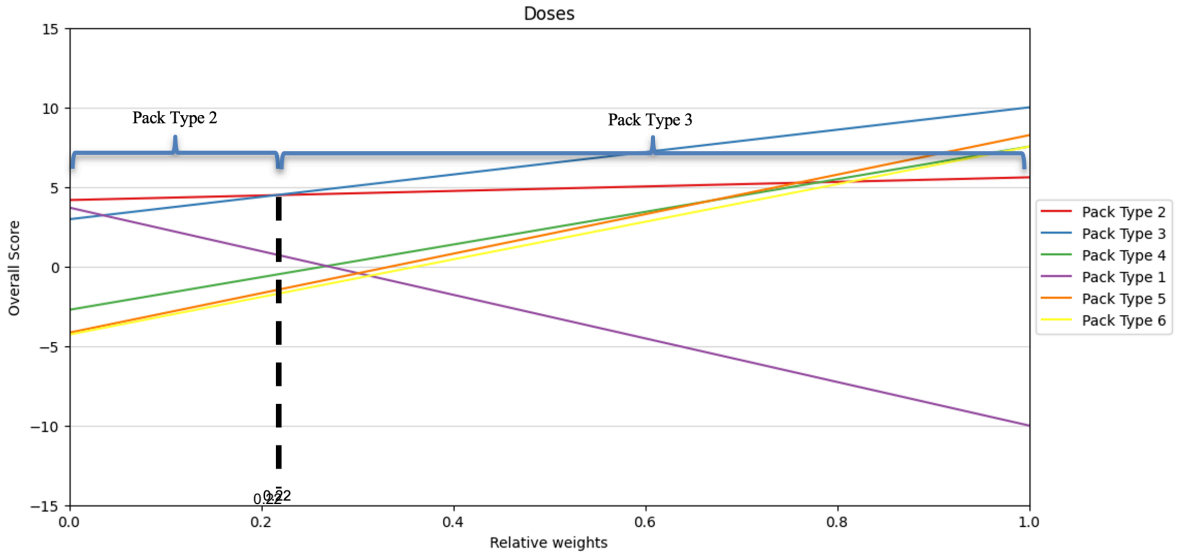
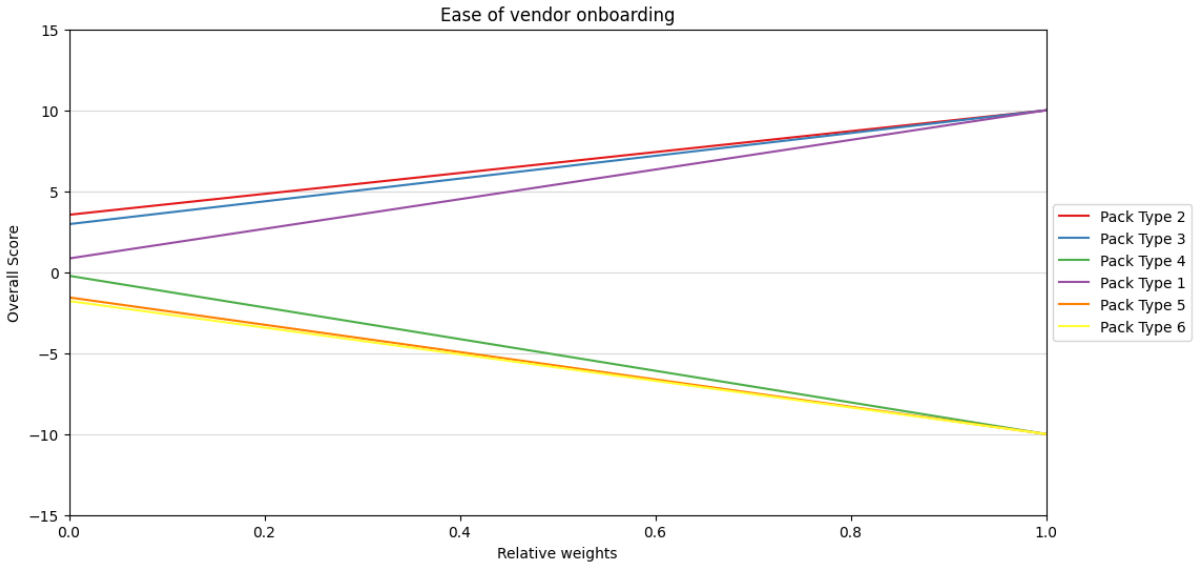



Figure 8 shows the overall value of each pack type or option as a function of the weight of criterion- ease of vendor onboarding. The vertical line shows the baseline weight for validation time (0.26) with Pack Type 3 being the best one overall at this weight level. Even if the relative weight of validation time was increased, Pack Type 3 would remain the most preferred option.

**Figure 8: C2 Cluster Sensitivity Analysis- Ease of Vendor Onboarding**



Therefore, it can be concluded that the solution (choice of pack type) is quite robust and only Pack Type 3 and Pack Type 4 should be considered regardless of the relative weights of the different criteria in the decision-making model.

Results and findings discussed above are for the cluster C2. A similar analysis was conducted for all the remaining clusters: C1, C3, C4, C5 and C6. Detailed results and sensitivity analysis plots have been presented in Appendices section of this document.

## 5. DISCUSSION AND CONCLUSION

The capstone project provides a framework for the selecting thermo packages supporting global vaccine distribution as well as to non-cold chain and other industries. The project began with scoping and a comprehensive literature review, followed by the development of a methodology that can be applied in a wide variety of environments across industries and companies.

The results and analysis chapter describes the application of the steps described in the methodology section. The clustering process provides an excellent way to identify similarities and differences among the lanes in the concerned organization's network. This clustering approach allows for the optimization of organization's transportation network, which can help in making operational decisions efficiently. The Multi Attribute Value Analysis method was used to reach robust solutions for each of the clusters developed thus far. The final step included conducting sensitivity analysis of top criteria to understand the robustness of the solution.

The significance of the findings of this study is multifold. Firstly, the clustering approach can help organizations to see their global network in a manageable, similar-looking groups, which can lead to improved operational efficiency and cost savings. Secondly, this method is a highly valuable and adaptable method that can be employed to identify the most robust option in various contexts. Its significance lies not only in its general application but also in its relevance to this study. This research can effectively address current product and network requirements, while also providing flexibility to accommodate future changes in the network or product line. Its versatility makes it a powerful tool to target specific needs and easily adapt to evolving circumstances.

Additionally, the findings from this study can be applied to a variety of industries and products, not just limited to the biotech industry. This framework can be used in any organization with a large network of lanes, allowing them to identify similarities and differences and optimizing how goods are moved throughout the network. Moreover, the Multi Attribute Value Analysis

method can be used to select the most robust option for any set of concepts and criteria, making it useful in decision-making processes across various industries.

In summary, this capstone project offers biotech companies and other industries alike a game-changing framework for selecting the ideal packaging solution. With its broad applicability and far-reaching impact, the methodology employed can revolutionize operations and unlock substantial gains in both efficiency and cost reduction.

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## APPENDIX A

C1 Cluster results and sensitivity analysis

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| No of doses per pallet | 18000 | 17214 | 21558 | 19122 | 19830 | 19122 | 90 |
| Reusability (times) | 0 | 0 | 50 | 30 | 30 | 30 | 40 |
| Cost of packaging (each time) | 1305 | 1440 | 1360 | 832 | 1470 | 1605 | 100 |
| Lead times first order (days) | 15 | 15 | 15 | 21 | 21 | 21 | 80 |
| Lead times subsequent order (days) | 7 | 7 | 7 | 15 | 15 | 15 | 85 |
| Ease of vendor onboarding (1/0) | 1 | 1 | 1 | 0 | 0 | 0 | 70 |
| Carbon Footprint (Kgs) | 215 | 215 | 10 | 10 | 10 | 10 | 40 |
| Validation Time (hours) | 96 | 96 | 120 | 96 | 130 | 140 | 60 |

Table A1: C1 Performance Matrix

| Criteria/Concepts | PackType1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| No of doses per pallet | -6 | -10 | 10 | -1 | 2 | -1 | 16% |
| Reusability (times) | -10 | -10 | 10 | 2 | 2 | 2 | 7% |
| Cost of packaging (each time) | -2 | -6 | -4 | 10 | -7 | -10 | 18% |
| Lead times first order (days) | 10 | 10 | 10 | -10 | -10 | -10 | 14% |
| Lead times subsequent order (days) | 10 | 10 | 10 | -10 | -10 | -10 | 15% |
| Ease of vendor onboarding (1/0) | 10 | 10 | 10 | -10 | -10 | -10 | 12% |
| Carbon Footprint (Kgs) | -10 | -10 | 10 | 10 | 10 | 10 | 7% |
| Validation Time (hours) | -10 | -10 | 1 | -10 | 5 | 10 | 11% |
| Final Scores | 0.3 | -1.2 | 7.4 | -3.6 | -4.5 | -4.9 | |

Table A2: C1 Decision Matrix

***Sensitivity Analysis***

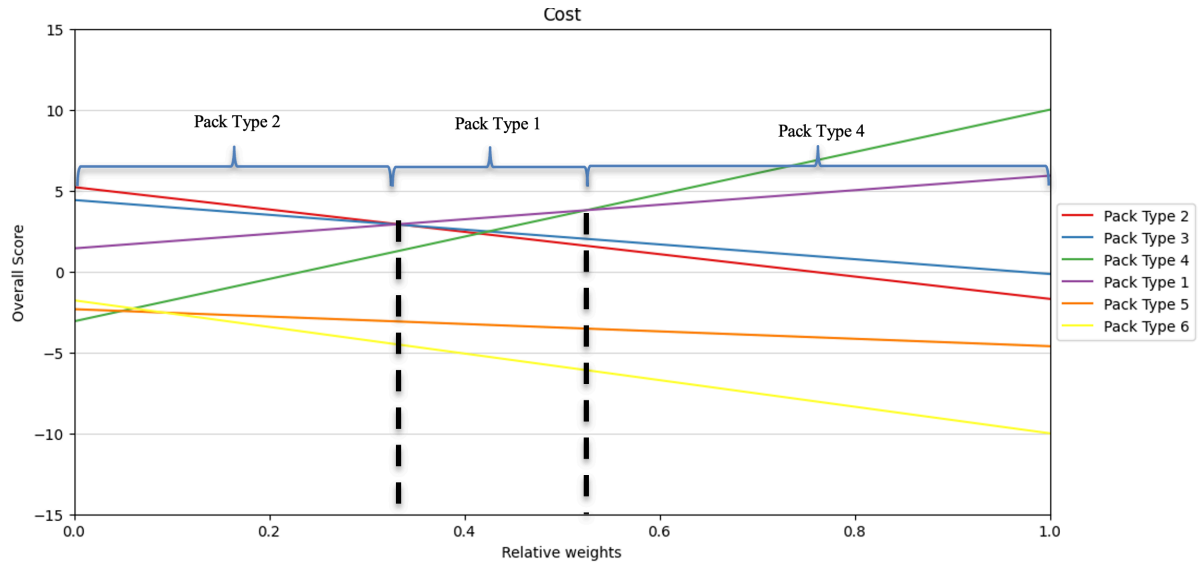


Figure A1: C1 Cluster Sensitivity Analysis – Cost of packaging

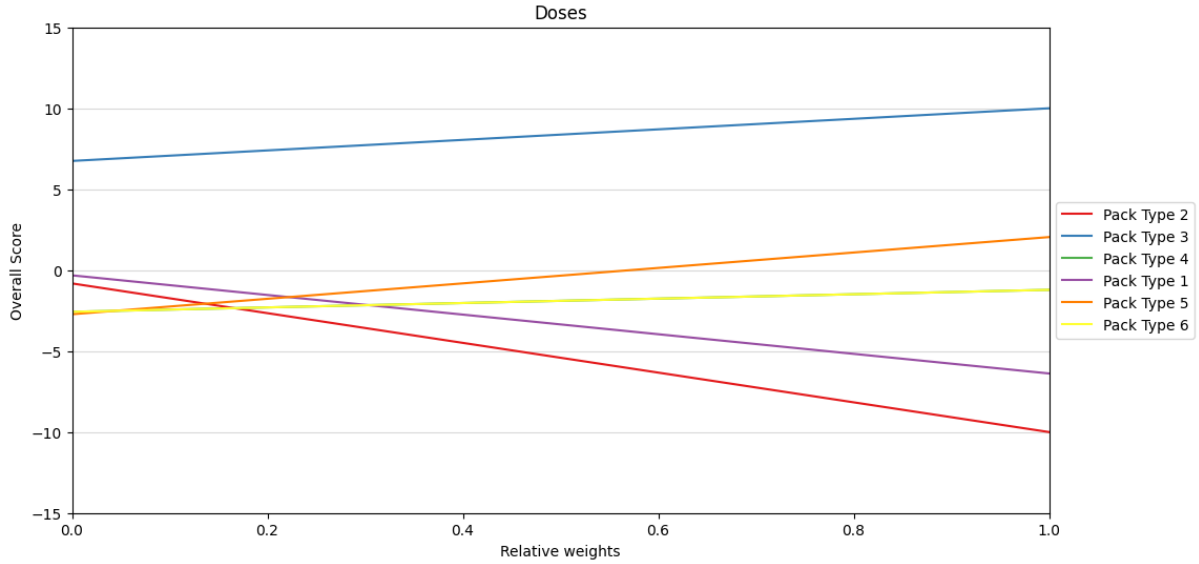


Figure A2: C1 Cluster Sensitivity Analysis – Number of doses

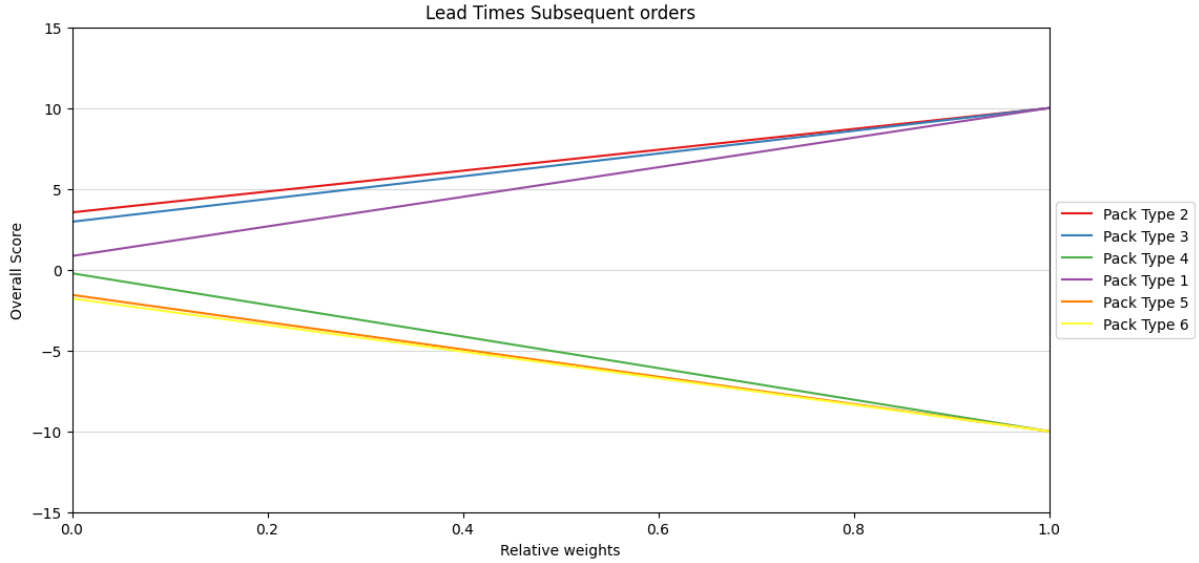


Figure A3: C1 Cluster Sensitivity Analysis – Lead time subsequent orders

## APPENDIX B

C3 Cluster results and sensitivity analysis

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Swing Weights |
|---|---|---|---|---|---|
| No of doses per pallet | 4800 | 4200 | 3900 | 2625 | 100 |
| Reusability (times) | 0 | 0 | 0 | 0 | 0 |
| Cost of packaging (each time) | 54 | 48 | 35 | 29 | 90 |
| Lead times first order (days) | 21 | 15 | 15 | 15 | 80 |
| Lead times subsequent order(days) | 10 | 7 | 7 | 7 | 85 |
| Ease of vendor onboarding (1/0) | 1 | 1 | 1 | 1 | 90 |
| Validation Time (hours) | 90 | 48 | 48 | 48 | 70 |

Table B1: C3 Performance Matrix

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Swing Weights |
|---|---|---|---|---|---|
| No of doses per pallet | 10 | 4 | 2 | -10 | 19% |
| Reusability (times) | 0 | 0 | 0 | 0 | 0% |
| Cost of packaging (each time) | -10 | -5 | 5 | 10 | 17% |
| Lead times first order (days) | -10 | 10 | 10 | 10 | 16% |
| Lead times subsequent order(days) | -10 | 10 | 10 | 10 | 17% |
| Ease of vendor onboarding (1/0) | 0 | 0 | 0 | 0 | 17% |
| Validation Time (hours) | 10 | -10 | -10 | -10 | 14% |
| Final Scores | -1.7 | 1.8 | 3.1 | 1.7 | |

Table B2: C3 Decision Matrix

## *Sensitivity Analysis*

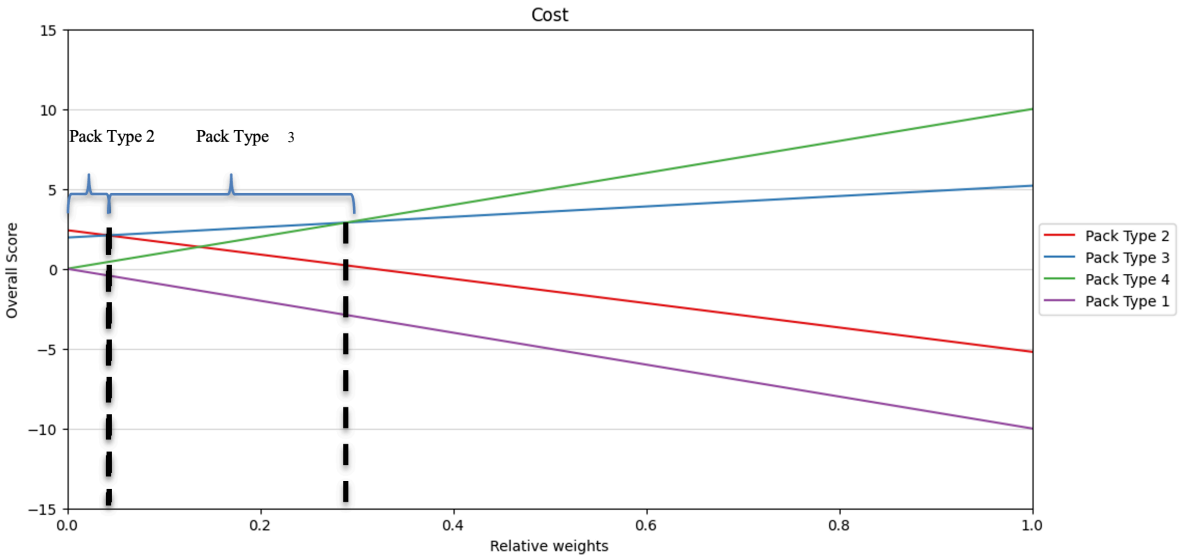


Figure B1: C3 Cluster Sensitivity Analysis – Cost of packaging

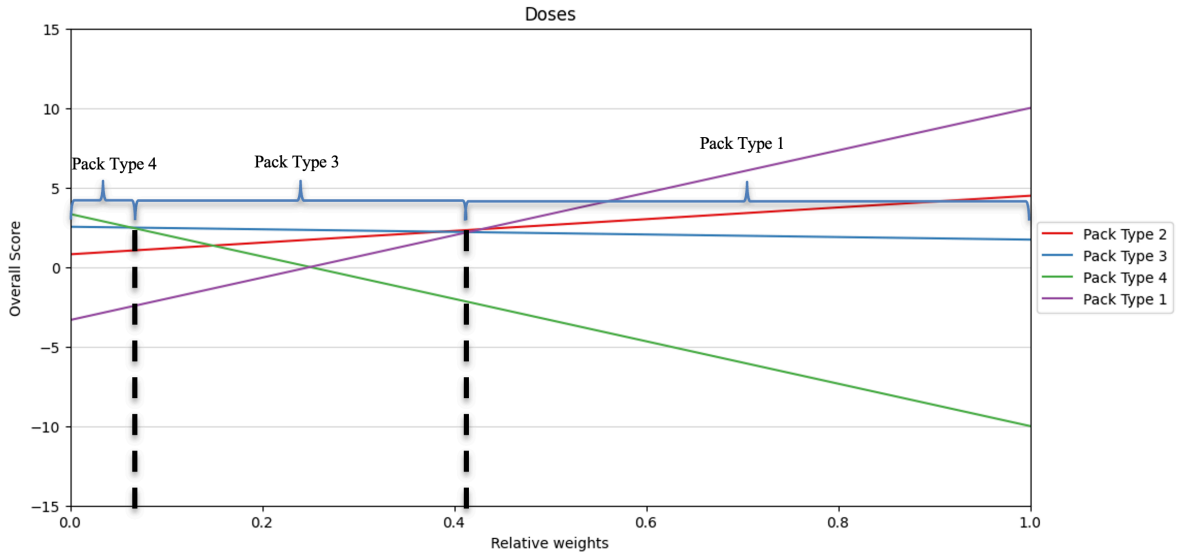


Figure B2: C3 Cluster Sensitivity Analysis – Number of doses

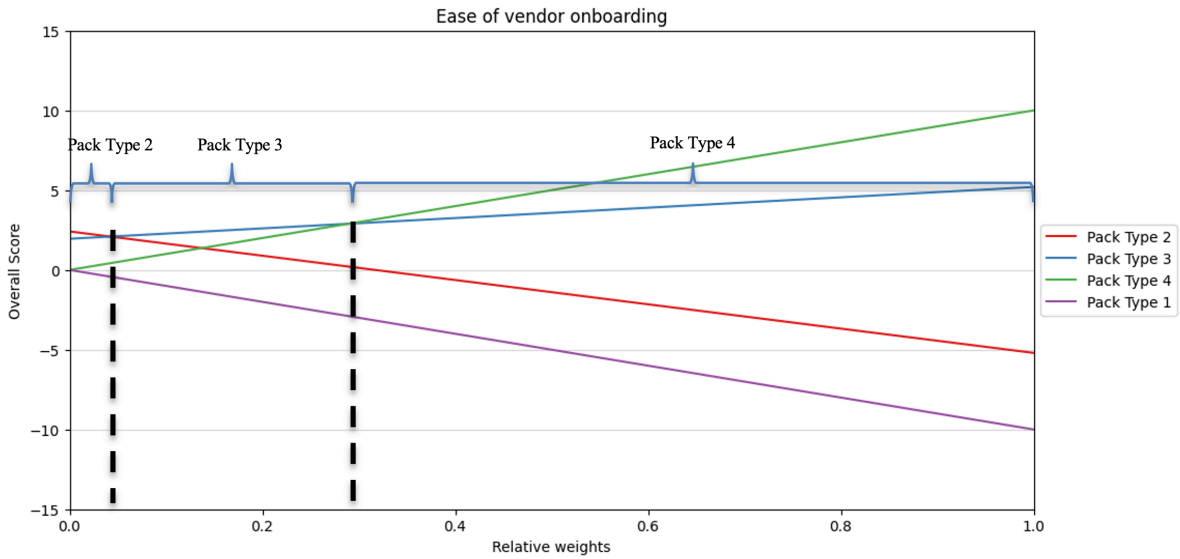


Figure B3: C3 Cluster Sensitivity Analysis – Ease of vendor onboarding

Discussion on sensitivity Analysis:

The Sensitivity Analysis in Figure B1 shows the overall value of different pack types or options based on the weight of criterion-cost of packaging. Each colour line represents the overall score of a pack type with the relative weight of cost of packaging ranging from 0 to 1. The findings revealed that as the weight for cost of packaging increased from 0 to 0.03, the preferred choice was Pack Type 2. As the weight increased further to 0.3, the preferred choice became Pack Type 3. Finally, after 0.3 weight for cost of packaging, the choice consistently remained Pack Type 4.

The Sensitivity Analysis in Figure B2 shows the overall value of different pack types or options based on the weight of criterion-Number of doses. Each color line represents the overall score of a pack type with the relative weight of number of doses ranging from 0 to 1. The findings revealed that as the weight for cost of packaging increased from 0 to 0.05, the preferred choice was Pack Type 4. As the weight increased further to 0.41, the preferred choice became Pack Type 3 and the choice consistently remained Pack Type 1 thereafter.

Figure B3 shows the overall value of each pack type or option as a function of the weight of criterion- ease of vendor onboarding. Each color line represents the overall score of a pack type with the relative weight of number of doses ranging from 0 to 1. The findings revealed that as

the weight for cost of packaging increased from 0 to 0.03, the preferred choice was Pack Type 2. As the weight increased further to 0.3, the preferred choice became Pack Type 3 and the choice consistently remained Pack Type 4 thereafter.

## APPENDIX C

C4 Cluster results and sensitivity analysis

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Pack Type 7 | Pack Type 8 | Pack Type 9 | Swing Weights |
|---|---|---|---|---|---|---|---|---|---|---|
| No of doses per pallet | 4800 | 2250 | 3600 | 3600 | 5250 | 3000 | 3500 | 6000 | 6000 | 100 |
| Reusability (times) | 0 | 190 | 190 | 190 | 190 | 195 | 195 | 195 | 195 | 5 |
| Cost of packaging (each time) | 483 | 180 | 195 | 260 | 625 | 192 | 257 | 333 | 537 | 0 |
| Lead times first order(days) | 15 | 15 | 15 | 15 | 15 | 21 | 21 | 21 | 21 | 0 |
| Lead times subsequent order(days) | 7 | 7 | 7 | 7 | 7 | 15 | 15 | 15 | 15 | 75 |
| Ease of vendor onboarding (1/0) | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 80 |
| Validation Time (hours) | 90 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 90 |

Table C1: C4 Performance Matrix

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Pack Type 7 | Pack Type 8 | Pack Type 9 | Swing Weights |
|---|---|---|---|---|---|---|---|---|---|---|
| No of doses per pallet | -4 | 2 | 10 | 4 | -10 | 7 | 4 | 10 | -1 | 29% |
| Reusability (times) | -10 | 9 | 9 | 9 | 9 | 10 | 10 | 10 | 10 | 1% |
| Cost of packaging (each time) | -4 | 10 | 9 | 6 | -10 | 9 | 7 | 3 | -6 | 0% |
| Lead times first order(days) | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | 0% |
| Lead times subsequent order(days) | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | 21% |
| Ease of vendor onboarding (1/0) | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | 23% |
| Validation Time (hours) | -10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 26% |
| Final Scores | 0.5 | 7.7 | 10.0 | 8.4 | 4.3 | 0.3 | -0.6 | 1.0 | -2.0 | |

Table C2:C4 Decision Matrix

***Sensitivity Analysis***

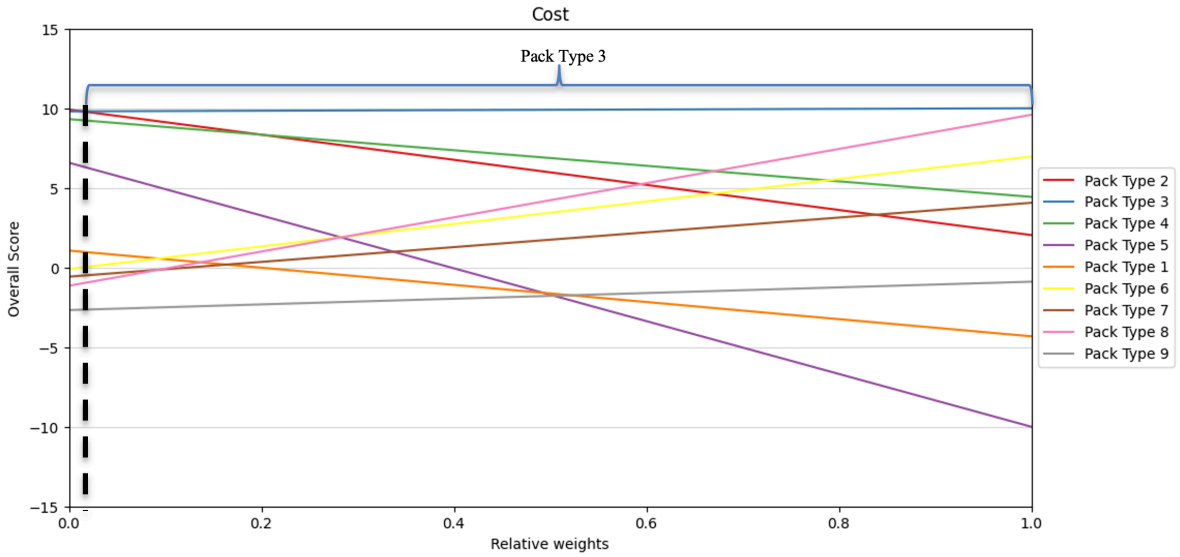


Figure C1: C4 Cluster Sensitivity Analysis – Cost of packaging

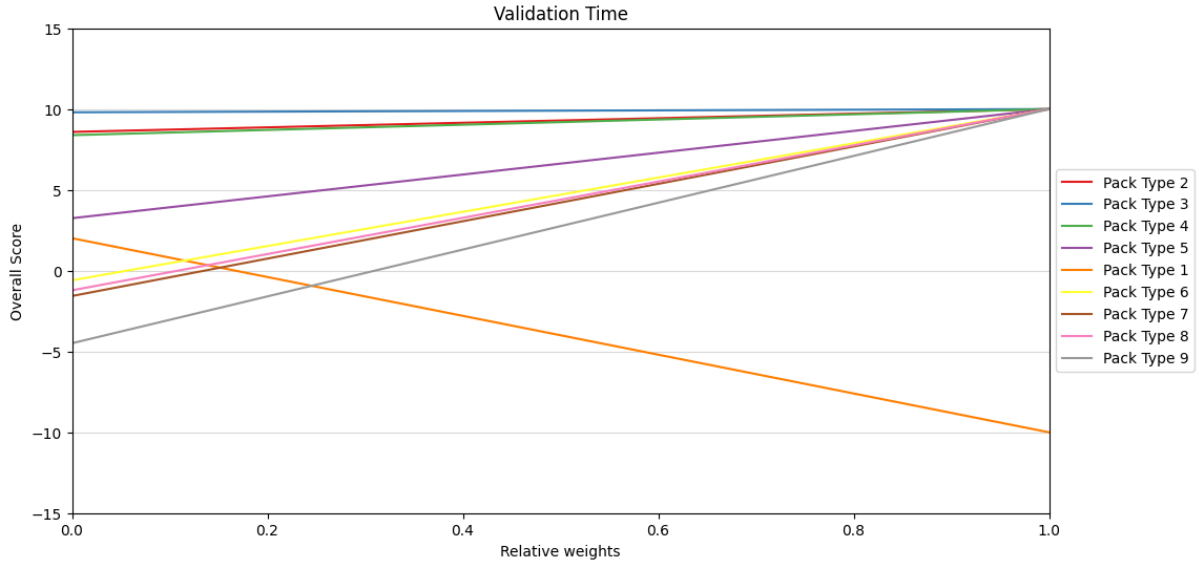


Figure C2: C4 Cluster Sensitivity Analysis – Validation time

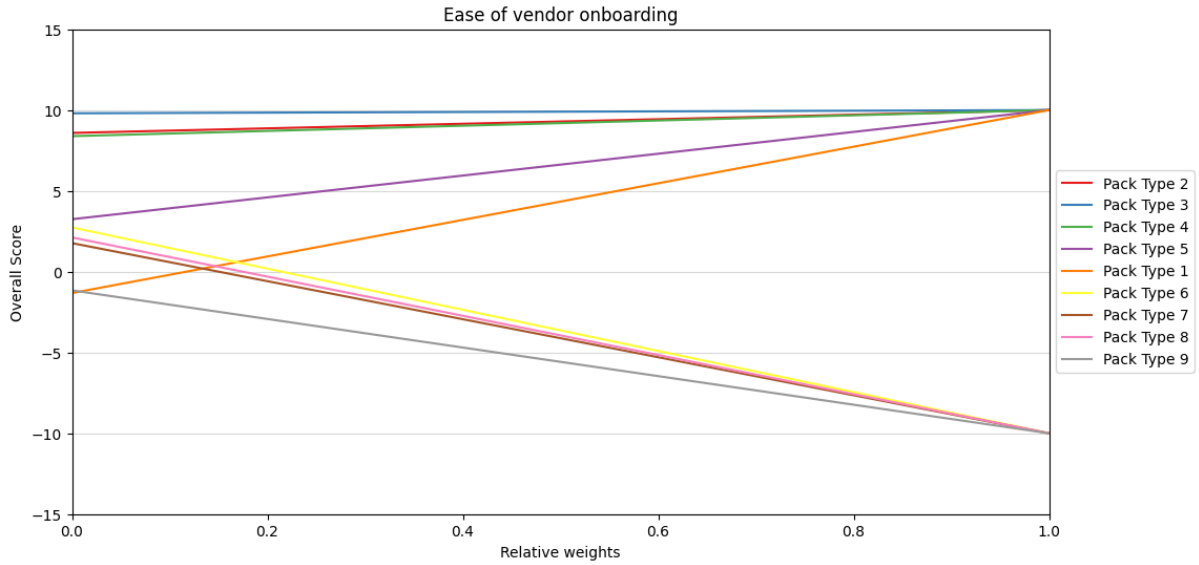


Figure C3: C4 Cluster Sensitivity Analysis – Ease of vendor onboarding

## APPENDIX D

C5 Cluster results and sensitivity analysis

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Pack Type 7 | Pack Type 8 | Pack Type 9 | Pack Type 10 | Pack Type 11 | Pack Type 12 | Pack Type 13 | Pack Type 14 | Pack Type 15 | Pack Type 16 | Pack Type 17 | Pack Type 18 | Pack Type 19 | Pack Type 20 | Pack Type 21 | Swing Weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No of doses per pallet | 4800 | 2250 | 3600 | 3600 | 5250 | 2250 | 3600 | 3600 | 5250 | 5600 | 4200 | 3900 | 2625 | 3000 | 3500 | 6000 | 6000 | 1800 | 3150 | 4500 | 4500 | 100 |
| Reusability (times) | 0 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 0 | 0 | 0 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 5 |
| Cost of packaging(each time) | 800 | 180 | 195 | 260 | 625 | 220 | 255 | 300 | 640 | 710 | 160 | 70 | 55 | 192 | 257 | 333 | 537 | 365 | 474 | 569 | 791 | 0 |
| Lead times first order(days) | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 9 |
| Lead times subsequent order(days) | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 10 |
| Ease of vendor onboarding(1/0) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 75 |
| Validation Time(hours) | 90 | 96 | 96 | 96 | 96 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 96 | 96 | 96 | 96 | 120 | 120 | 120 | 120 | 90 |

Table D1:C5 Performance Matrix

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Pack Type 7 | Pack Type 8 | Pack Type 9 | Pack Type 10 | Pack Type 11 | Pack Type 12 | Pack Type 13 | Pack Type 14 | Pack Type 15 | Pack Type 16 | Pack Type 17 | Pack Type 18 | Pack Type 19 | Pack Type 20 | Pack Type 21 | Swing Weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No of doses per pallet | 4 | -8 | -1 | -1 | 6 | -8 | -1 | -1 | 6 | 8 | 1 | 0 | -6 | -4 | -2 | 10 | 10 | -10 | -4 | 3 | 3 | 34.60% |
| Reusability (times) | -10 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | -10 | -10 | -10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 1.73% |
| Cost of packaging(each time) | 11 | 7 | 6 | 4 | -5 | 6 | 5 | 3 | -6 | -8 | 7 | 10 | 10 | 6 | 5 | 2 | -3 | 2 | -1 | -4 | -10 | 0.00% |
| Lead times first order(days) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | 3.11% |
| Lead times subsequent order(days) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | 3.46% |
| Ease of vendor onboarding(1/0) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | -10 | 25.95% |
| Validation Time(hours) | -10 | -6 | -6 | -6 | -6 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | -6 | -6 | -6 | -6 | 10 | 10 | 10 | 10 | 31.14% |
| Final Scores: Novavax Team | -5.4 | -5.3 | -3.1 | -3.1 | -0.4 | 10.7 | 12.9 | 12.9 | 15.6 | 16.2 | 13.6 | 13.1 | 11.0 | -10.6 | -9.7 | -5.6 | -5.6 | 3.5 | 5.7 | 7.9 | 7.9 | |

Table D2: C5 Decision Matrix

## *Sensitivity Analysis*

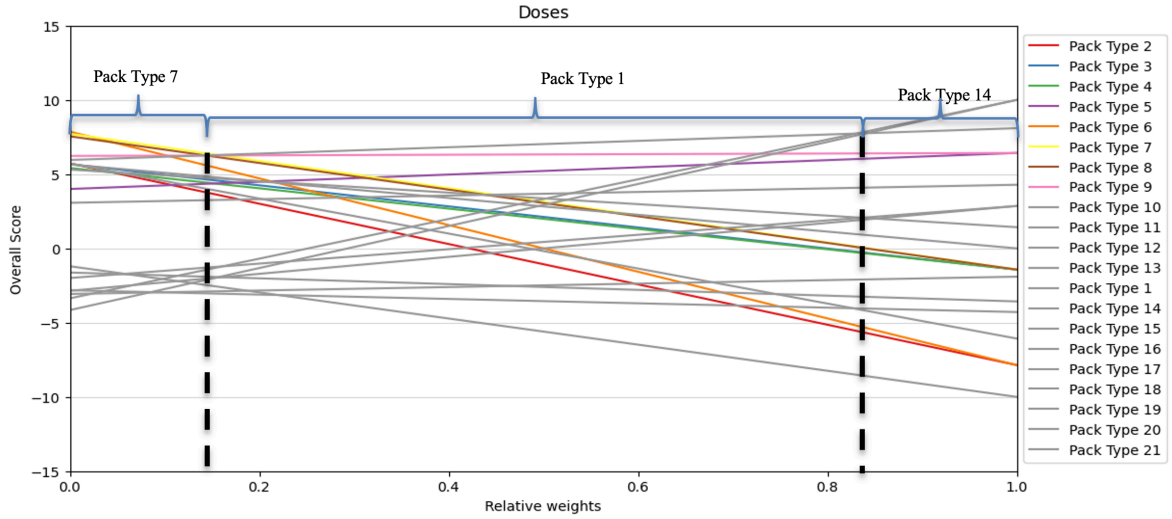


Figure D1: C5 Cluster Sensitivity Analysis – Number of doses

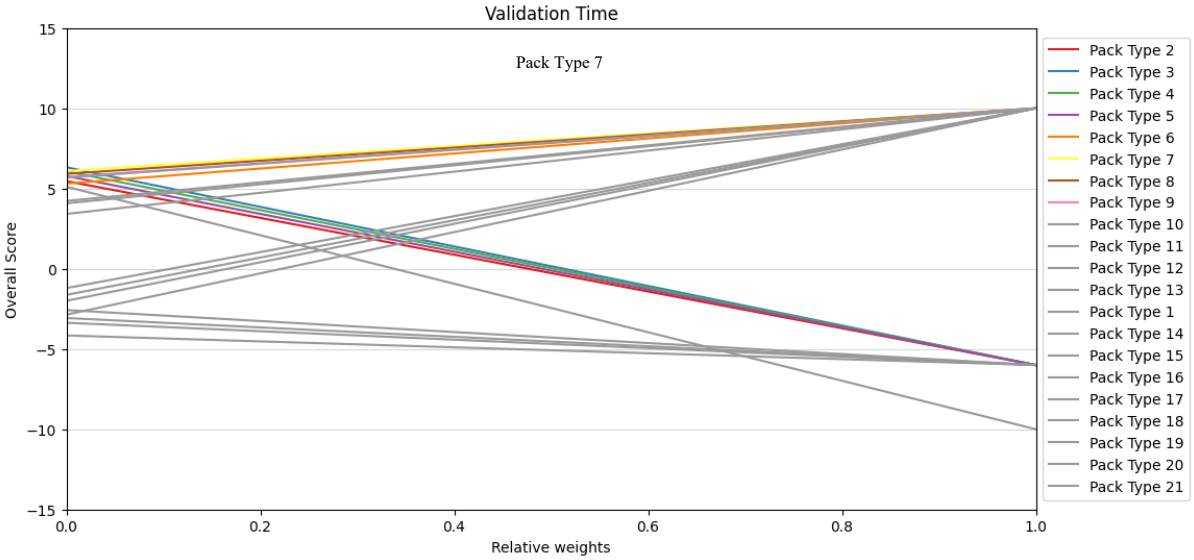


Figure D2: C5 Cluster Sensitivity Analysis – Validation time

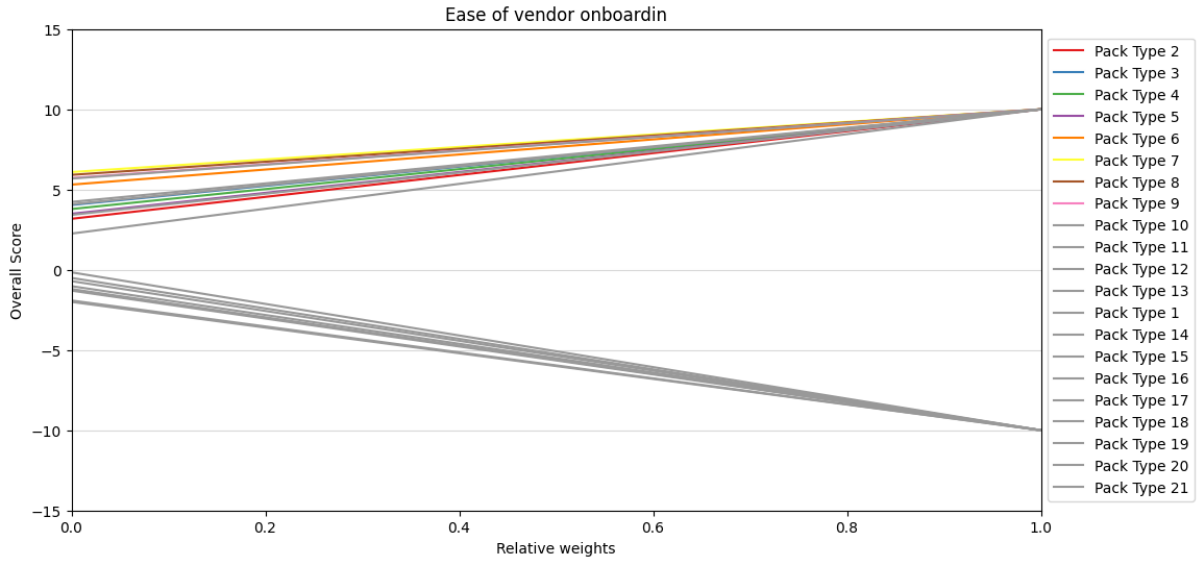


Figure D3: C5 Cluster Sensitivity Analysis –Ease of vendor onboarding

## APPENDIX E

C6 Cluster results and sensitivity analysis

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| No of doses per pallet | 18000 | 17214 | 21558 | 19122 | 19830 | 19122 | 90 |
| Reusability (times) | 0 | 0 | 50 | 30 | 30 | 30 | 40 |
| Cost of packaging (each time) | 1305 | 1440 | 1360 | 832 | 1470 | 1605 | 100 |
| Lead times first order(days) | 15 | 15 | 15 | 21 | 21 | 21 | 80 |
| Lead times subsequent order(days) | 7 | 7 | 7 | 15 | 15 | 15 | 85 |
| Ease of vendor onboarding (1/0) | 1 | 1 | 1 | 0 | 0 | 0 | 70 |
| Carbon Footprint (Kgs) | 215 | 215 | 10 | 10 | 10 | 10 | 40 |
| Validation Time (hours) | 96 | 96 | 120 | 96 | 130 | 140 | 60 |

Table E1: C6 Performance Matrix

| Criteria/Concepts | Pack Type 1 (DATUM) | Pack Type 2 | Pack Type 3 | Pack Type 4 | Pack Type 5 | Pack Type 6 | Swing Weights |
|---|---|---|---|---|---|---|---|
| No of doses per pallet | -6 | -10 | 10 | -1 | 2 | -1 | 16% |
| Reusability (times) | -10 | -10 | 10 | 2 | 2 | 2 | 7% |
| Cost of packaging (each time) | -2 | -6 | -4 | 10 | -7 | -10 | 18% |
| Lead times first order(days) | 10 | 10 | 10 | -10 | -10 | -10 | 14% |
| Lead times subsequent order(days) | 10 | 10 | 10 | -10 | -10 | -10 | 15% |
| Ease of vendor onboarding (1/0) | 10 | 10 | 10 | -10 | -10 | -10 | 12% |
| Carbon Footprint (Kgs) | -10 | -10 | 10 | 10 | 10 | 10 | 7% |
| Validation Time (hours) | -10 | -10 | 1 | -10 | 5 | 10 | 11% |

Table E2: C6 Decision Matrix

## *Sensitivity Analysis*

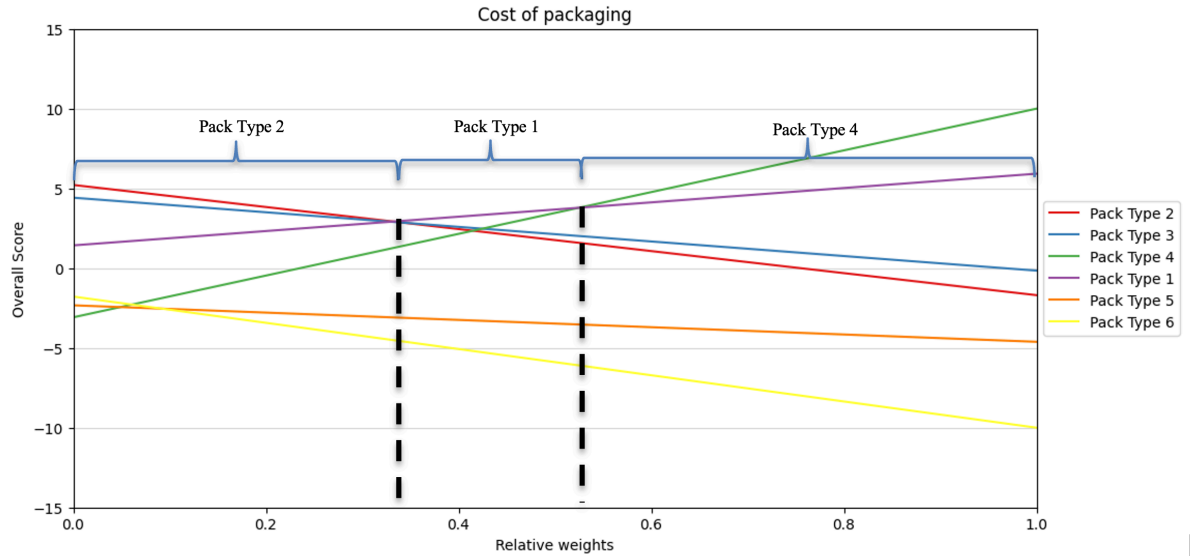


Figure E1: C6 Cluster Sensitivity Analysis –Cost of packaging

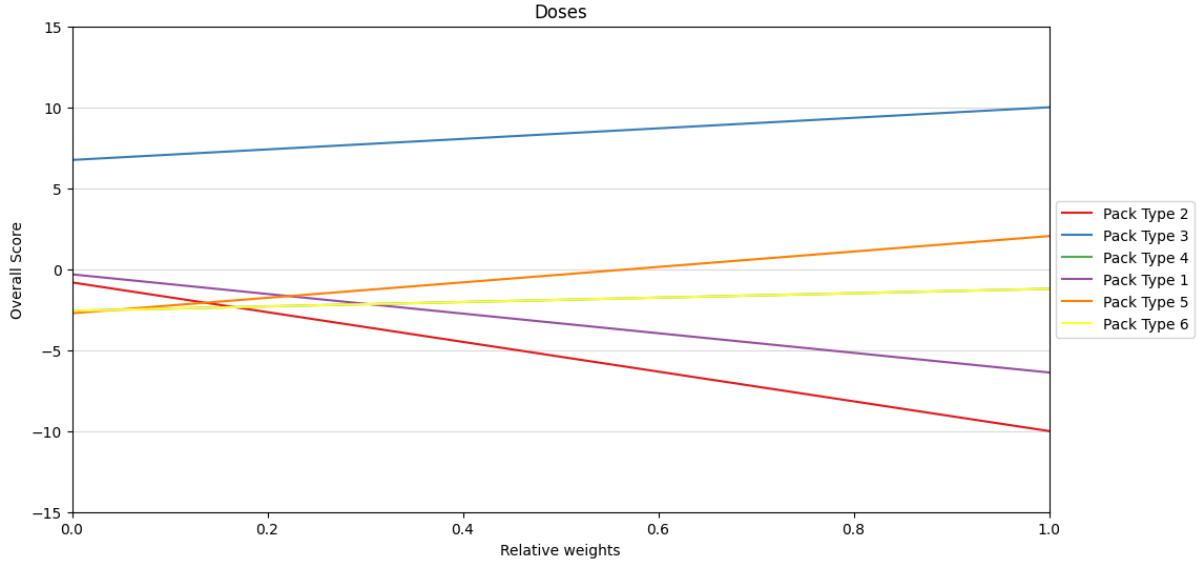


Figure E2: C6 Cluster Sensitivity Analysis –Number of doses

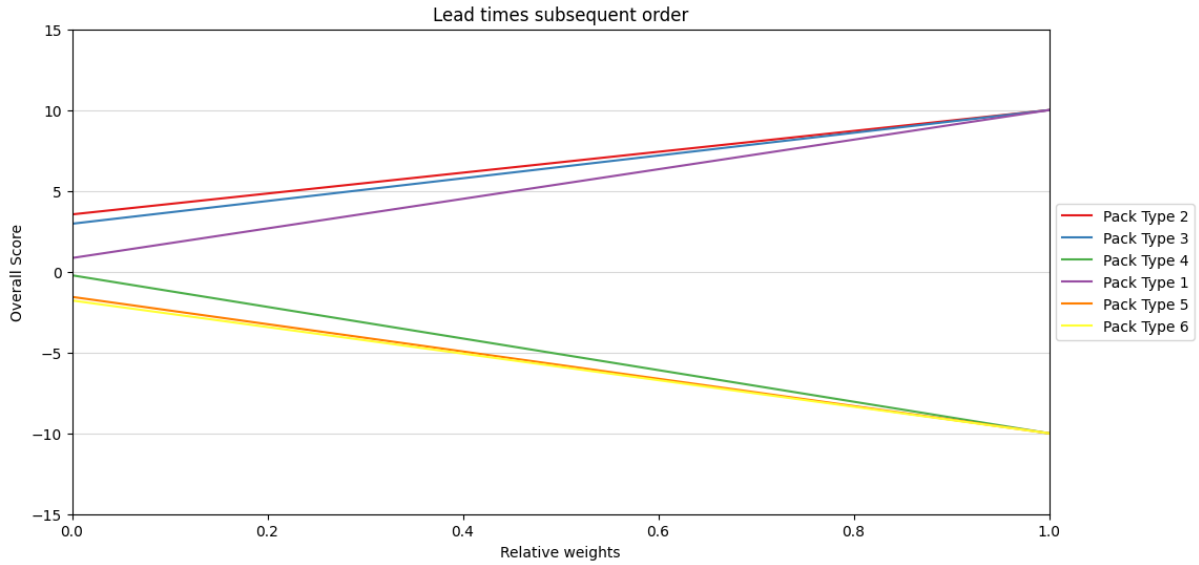


Figure E3: C6 Cluster Sensitivity Analysis –Lead time subsequent orders