AN OPERATIONAL CONCEPT OF AN IOT SYSTEM FOR THE PALLETIZED DISTRIBUTION SUPPLY CHAIN

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ABSTRACT

In recent years, Internet-of-Things technology (IoT) has been the subject of research in a diverse field of applications, given its essential role in transitioning society towards a more interconnected paradigm of conducting manufacturing, logistics, services, and business, what is also known as Industry 4.0. Consistent with this line of research, this project addresses the application of IoT in distribution packaging as a way to better understand supply chain conditions.

Specifically, this work presents an operational concept for a system that implements IoT technology in the pallets that are used to move products along supply chains and serve as a vehicle to gain insight into the conditions experienced by products and unit loads. The development of this operational concept leverages a systems engineering framework to discover user needs, and stakeholders, and apply model-based systems engineering to create system models that capture expected system behavior and the outputs necessary to create value for the user.

A semi structured interview was conducted with eleven companies in order to discover user needs related to their packaging during distribution processes in their supply chain. A system operational concept was developed through use cases, concept of operations, and formal modeling using Cameo System Modeling Software. A review of sensor and communication technologies is presented, as well as a description of the challenges and future research opportunities for the proposed operational concept in distribution packaging.

The application of systems engineering framework, and model-based systems engineering to the distribution packaging domain brings clarity to problem formulation in order to lay-out solid value propositions for the adoption of IoT technologies, and to ensure successful realization of systems that achieve customer satisfaction.

This work offers three main contributions. First, it provides an identification and description of the needs that industrial companies have in relation to their product and packaging performance during distribution operations. Secondly, it shows how a systems-based approach, leveraging on model-based systems engineering can be employed to conceptualize systems that use innovative technologies like IoT in the domain of distribution packaging. Third, it provides an overview of open research challenges and practical considerations for the implementation of IoT technology in the field of distribution packaging.

AN OPERATIONAL CONCEPT PROPOSAL OF AN IOT SYSTEM FOR THE PALLETIZED DISTRIBUTION SUPPLY CHAIN

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GENERAL AUDIENCE ABSTRACT

In 2007, The World Bank published a study which states that “eighty percent of US trade is carried on pallets” (Raballand & Aldaz-Carroll, 2007). Furthermore, in the year 2015, a report estimated that there would be 2.6 billion pallets circulating in the United States by the year 2017 (Freedonia Group, 2015). Pallets are ubiquitous and a key component of distribution operations in supply chains, as they transport goods, and are the main interface that connects material handling equipment and packaged products (White & Hamner, 2005). Based on that distinctive characteristic, this study contends that pallet can be used as a window to gain insight into the realities of what is experienced by products and packaging during distribution. This can be done by using sensors imbedded in pallets to capture data of interest about the physical conditions in the supply chains, which opens the potential for more customized and optimized packaging design, supported by more reliable and representative information. This idea is particularly relevant, as established protocols for packaging testing are limited in their capacity to accurately simulate the real-world conditions that occur in the supply chain. This has resulted in suboptimal packaging design (Rouillard, 2008) that decreases the efficiency of logistics operations.

This study found that industrial companies are most concerned with avoiding damage that their products can suffer during transportation as a result of temperature, relative humidity, shock, and vibration. Thus, it is necessary to gather data about these distribution parameters for product shipments. Using a model-based system engineering approach, an operational concept is proposed to show what is needed from a system to be able to track these parameters. Furthermore, a review of current available technology for IoT is presented, as well as an examination of the challenges posed to the realization of the proposed operational concept, including factors like cybersecurity, and energy resources constraints.

This work offers three main contributions. First, it provides an identification and description of the needs that industrial companies have in relation to their product and packaging performance during distribution operations. Secondly, it shows how a systems-based approach, leveraging on model-based systems engineering can be employed to conceptualize systems that use innovative technologies like IoT in the domain of distribution packaging. Third, it provides an overview of open research challenges and practical considerations for the implementation of IoT technology in the field of distribution packaging.

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I. INTRODUCTION

The emergence of novel technologies like cyber-physical systems is promising to revolutionize the logistics and supply chain industry. The internet of things (IoT) aims to integrate the physical world with computational systems by embedding objects, such as pallets, containers and packages, with sensors and software that can exchange collected data with cloud platforms and other smart objects, enabling opportunities to develop new applications that will improve the efficiency and performance of logistics and supply chain operations (Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012). IoT technology allows the virtualization of the entire supply chain. This enables stakeholders to track and trace the flow of goods along the supply chain and obtain valuable information like the quality status of products and allows for better planning and synchronization.

Although much research and interest has already been given to issues present in food supply chains and how IoT can integrate and improve performance and reduce weaknesses, little is known about other products' supply chains nor what issues are costing money to companies that IoT might be able to address. This research aimed to determine the users' needs in regard to distribution parameters in the transportation of goods, that could be helped by IoT infrastructure.

The implementation of IoT technologies entail greater interaction among the physical, and virtual elements in the supply chain, which increase overall complexity. This makes necessary the adoption of an approach to tackle this emergent complexity in order to ensure that new IoT systems in supply chain are effective in responding to genuine needs and that they deliver value. This project applies a systems engineering framework to the development of an operational concept of an IoT system for the palletized distribution supply chain and leverages on model-based systems engineering to elicit system requirements.

Within the domain of IoT and the palletized distribution supply chain, the focus of this project is the right formulation of the system problem, which sets a sound foundation upon which a specific system solution can be developed.

According to Ben- Daya et al. (2017), there is a need for research that proposes model solutions that address supply chain problems from an IoT standpoint, with particular focus on the new tools required to manage these virtualized supply chains. The new tools needed will involve the collection of massive amounts of data and the interaction of all the connected things in the IoT network.

II. LITERATURE REVIEW

A. PALLETS

Pallets are portable and rigid platforms commonly used as a base for assembling, stacking, handling, and transporting finished products and goods. This makes them a critical component for the distribution operations that impact the efficiency and sustainability of the supply chain (Carrano, Pazour, Roy, & Thorn, 2015; Elia & Gnoni, 2015).

One of the contributions of pallets is the increasing productivity of materials handling by allowing the movement of unit loads. A unit load is the consolidation of individual items in a single unit that can be stored or moved at one time, aiming the minimization of movements required to handle a definite quantity of load (Heragu & Ekren, 2009; S. Ray, 2008).

The wooden pallet was introduced the 1930's, and begun to be used massively during World War II, when the United States military used it to move and store vast amounts of material for the war effort. As labor costs increased, several industries looked for efficient ways to handle materials, causing the use of forklifts and pallets to grow steadily in the following post-war decades. By 1974, wood pallet production in the United States exceeded 205 million units (Eichler, 1976).

Manufacturing production and warehousing activities are related to the number of pallets used and produced yearly; estimates indicate that the number of pallets increased by 1,9% annually through 2019 to a total of 2.6 billion circulating units. This means an increase of 1.7% on pallet annual demand to 1.4 billion (Freedonia Group, 2015). The growth rate in the demand for pallets is a good proxy of the economy overall growth, as higher pallet demand represents more trade and industrial activity (Michel, 2014).

Pallets are generally made from wood and its derivatives, plastic and metal (M. White & Hamner, 2005). It is estimated that 84 % of the pallet stock in the United States in 2019 was made of wood, representing 93% in terms of unit sales. Wood is widely used across a great variety of industries due to its low cost and large durability. However, wooden pallets demand growth is expected to be outpaced by plastic and metal pallet demand, as plastic is gaining importance for the medical and food industry due to plastics resistance to insects, fungi and other biological organisms that have the potential to impact negatively the product innocuousness (Freedonia Group, 2015). Furthermore, metal pallets, representing the smallest share of unit sales, continue to be used in cases involving extremely heavy items and transportation of dangerous chemicals (Freedonia Group, 2015).

1. Classification of Pallets

The following classification of pallets is described in accordance with the uniform standard for wood pallets developed by the National Wooden and Pallet Association, and the pallet, slip sheets and other bases for unit loads standard developed by the American National Standard Association. Wooden pallets are classified according to seven basic aspects: classes, use categories, entry types, styles, top deck constructions, bottom deck constructions and sizes (National Wooden Pallet and Container Association, 2014).

The two fundamental classes of pallets are stringer and block pallets. Stringers are wood members that provide space between the top and bottom deck boards and define the length of the pallet (Clarke,2004) as cited by (Baker, 2016). Most pallets use three stringers, one in the middle of the pallet across the width and two exterior stringers on the sides of the pallet (Baker, 2016).

Figure 1. Stringer Pallet

In the case of block pallets, nine blocks are used to hold the top and bottom deck boards, then, the deck boards are fastened to the blocks, forming the solid pallet. Block pallet demand has been increasing in recent years due to its better performance regarding strength and durability when compared with stringer pallets (Baker, 2016).

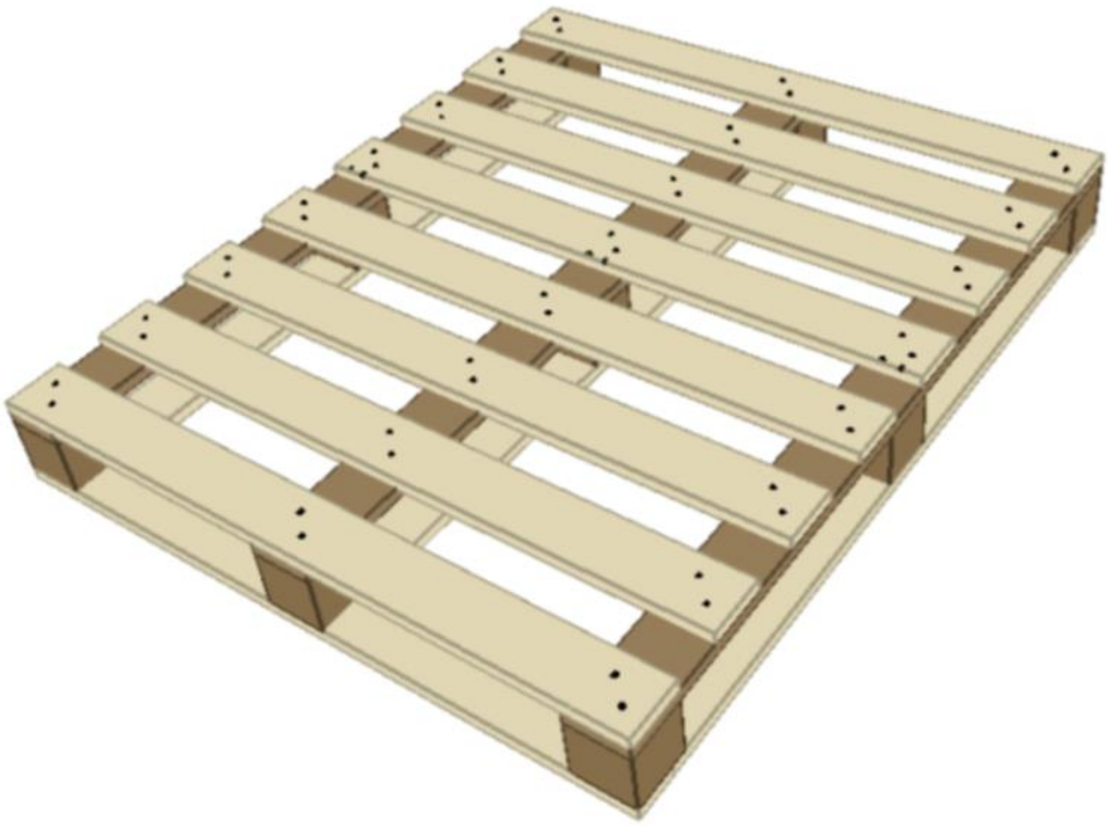

Figure 2. Block Pallet

The use category of the pallet is simply whether the pallet is intended to be used more than once, in which case it is known as re-usable pallet or if it is going to be discarded after the first trip, single-use pallet (National Wooden Pallet and Container Association, 2014).

The form of entry to the pallet is another way of classification. A two- way entry pallet will allow handling equipment entrance only through the back and front ends of the pallet. Usually this will be an unnotched stringer pallet. Notched stringer pallets and block pallets with overlapping panels or deck boards are partial four-way entrance pallets, which means that it can be accessed with a forklift on the four sides of the pallet; however, a pallet jack will only be able to access the pallet through the front and back ends. Finally, full four-way entry pallets have openings on both ends and sides that allow the entrance to standard handling equipment (National Wooden Pallet and Container Association, 2014).

The pallet style refers to the number of faces in the pallet. If there is only one face, then it is called a single-faced pallet, but if there are two faces, then it is known as a double-faced reversible, if the bottom and top deck boards are identical, or non – reversible otherwise. One disadvantage of double–face reversible pallets is their inability to be handled using a pallet jack due to lack of a place for the wheels of the jack to fit (American National Standard Association, 2016).

The way in which the top and bottom decks are built is another way to classify pallets, this includes deck board, deck board/ stringer board, panel and panel / stringer board for the top deck board and different configurations for the bottom deck board. These configurations can be unidirectional bottom deck boards oriented in only one direction, either length or width, overlapping bottom boards oriented in both directions, perimeter bottom deck boards containing butted boards and end boards and cruciform bottom deck boards containing butted end, and connector boards or panels with cutouts (National Wooden Pallet and Container Association, 2014).

All types of pallets can be found in multiple sizes. However, the International Standard Organization (ISO) recognizes six different sizes in different regions of the world, as presented in Table 1.

Table 1. Standard Pallet Sizes Recognized by the International Standard Organization (International Standard Organization, 2003) as cited by (Baker, 2016).

Continent	SI (mm)	US Customary (in)
Europe, Asia, India, Central and South America	1200 x 1000	47.24 x 39.37
Europe, Asia, India	1200 x 800	47.24 x 31.50
North America	1219 x 1016	48 x 40
Australia	1140 x 1140	44.88 x 44.88
Asia	1100 x 1100	43.30 x 43.30
North America, Europe, Asia	1067 x 1067	42 42

2. Pallet Materials and Manufacturing

2.1 Wood Pallets

The most dominant material used for pallet production is wood, due to its low material and production costs relative to its good performance, which is typically the most important consideration for companies when making decisions regarding pallet procurement. It is estimated that wooden pallets are used by 93% of the industry in the United States (Bond, 2018). The relative abundance of solid wood is another reason for its widely usage in pallet production and utilization (Buehlmann, Bumgardner, & Fluharty, 2009). Furthermore, the use of wood as the main raw material for pallet construction represents an important market for the wood fiber supply industry in the United States. It is estimated that 21,5% of the American lumber production in 2016 was used to either build new pallets or repair existing ones (Gerber, 2018).

Advantages for wooden pallets include their strength, stiffness, easy prototyping through software, and also integrate well in supply chains, given that many material handling equipment and packaging configurations are built and designed around the performance of wood pallets. Nevertheless, some disadvantages like the risk of damage to the product caused by fasteners and splinters, the loss of moisture, their proclivity to harbor insects and fungus and the great variability between pallets are all aspects that must be considered (Clarke, 2003).

Pallet production plants manufacture different types and sizes of pallets, and its main purpose is to transform the rough-sawn lumber into assembled pallet parts. Generally, the lumber first must be ripped to width, cut to length, surface planed and then assembled. Other operations might include chamfering and notching stringers (United States Forest Service, 1971). Figure 3 shows a process diagram that describes the wood pallet manufacturing process.

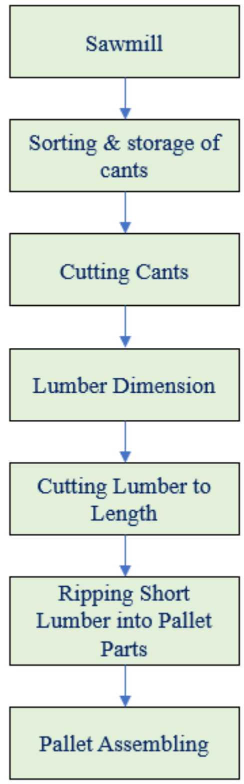

Figure 3. Pallet Manufacturing Process. Adapted from (Gomez, 2011).

Some degree of automation has been introduced in the pallet production operations since several decades ago as mass production caused manual assembling not to be feasible anymore (United States Forest Service, 1971). Different types of saws are known to have been used since the 1970's , as well as some gun-type nailers and staplers and other kinds of equipment (United States Forest Service, 1971).

Recently, pallet production operations have changed to adapt modern technologies and practices, including the use of robots to handle board feeding, component placement, pallet sortation, nailing, dismantling and other processes as well as more efficient production practices like lean manufacturing that aims to adopt a philosophy of continuous improvement and waste reduction (Brindley, 2017; Calabrese, 2005).

Automated and semi-automated lines have also been developed for pallet production. Storti, an Italian firm expert in the production of this kind of machinery offers several types of nailing lines, that can produce 2, 4, both 2 and 4 entry pallets, block and stringer pallets and whose productivity ranges from 1 pallet per minute to more than 9 pallets per minute, requiring from 0 to 4 people for their operation (Storti, 2018).

2.2 Plastic Pallets

Plastic is another material that has recently increased its usage in pallet production, with estimates indicating that 33% of industrial facilities in the United States use plastic pallets (Bond, 2018). Compliance and safety reasons, durability and customer demands are the top reasons for adopting plastic instead of wood in some applications (Michel, 2014).

Several polymeric materials are used to manufacture plastic pallets, polypropylene (PP) and polyethylene (PE) among the most common (Tepic et al., 2012). These polymers tend to be three to six times the price of wood per pound, resulting in much more expensive pallets (Clarke, 2003). Each kind of polymer presents different behaviors in terms of strength, elasticity, friction and other characteristics, thus they are usually manufactured in mixed proportions of polymers and other composites rather than as homo-polymers, in order to satisfy user needs (Tepic et al., 2012).

Typically, plastic pallets are used in automotive, dairy, pharmaceutical and beverage industries. Durability, cleanliness, no need for fasteners, weather resistance, and design potential are some of the reasons that encourage industries to implement the use of plastic pallets. On the other hand, their high price, low friction, low stiffness, the lack of repairing options, and fire safety ratings are some of the disadvantages that result from their use (Clarke, 2003).

Compression molding, foam molding, injection molding, profile extrusion, rotational molding and thermoforming are manufacturing methods used for plastic (Clarke, 2003). Using compression molding, heated raw materials are loaded into two-piece molds, a press closes the mold and forces the material to fill the cavities, creating the pallet. The materials used in this process can be wood fibers, synthetic resins, as well as plastics, the advantages of pallets produced with compression molding are their consistent strength, the uniform weight and sizes and the nestability of the pallet (LeBlanc & Richardson, 2003).

High pressure injection molding is another process used for pallet manufacturing. Most injection molding processes include the following steps: plastication, injection, packing, cooling, and molding resetting. Solid granules or pellets are plasticized and turned into polymer melt that is then forced into the mold during the injection stage by a rotating screw. Once the mold cavity is filled, the molten plastic starts cooling and contracting, so 1 to 10% more material is forced into the mold cavity. Once the cooling stage allows the material to solidify, creating the defined shape of the product being manufactured, the mold is opened and the molded part is removed, so the machine is ready for another cycle (Kazmer, 2009). Polyethylene and Polypropylene are the most used materials utilized for high-pressure injection molding pallets (LeBlanc & Richardson, 2003).

Low-pressure injection molding also known as structural foam molding is similar to high-pressure injection molding that differ during the injection phase, in which nitrogen gas is added to the polymer melt. Blowing agents activated by heat form a solid outer skin with a cellular core, which reduces de cost of raw material. This method also increases the strength to weight ratio of the pallet produced (LeBlanc & Richardson, 2003).

Thermoformed pallets can be manufactured using different methods, although the simplest one is called vacuum forming in which a thermoplastic sheet is heated in an oven using radiant heaters. When the sheet is deformable enough, vacuum is applied, removing the air between the sheet and a male mold (Kazmer, 2009; LeBlanc & Richardson, 2003). However, the most used method for thermoformed pallets is twin-sheet thermoforming, in which two ovens are required, one for a pre-heating cycle and the other for heating up to forming temperature. Two molds instead of one are also used at an upper and lower platen. When the first sheet is heated, it goes to the upper mold and the second sheet goes to the lower mold when heated, then, as vacuum is applied, the upper platen is lowered and the two molds are aligned, when pressure is also applied from the exterior of the molds (LeBlanc & Richardson, 2003).

Extrusion is a process used to create parts of pallets like boards and stringers that can then be assembled just as traditional wooden pallets are assembled using conventional equipment and methods (LeBlanc & Richardson, 2003). A heated barrel surrounds one or more rotating screws, to which the plastic pellets are fed. The material is molted when is compressed forward by the screw and then reaches the outlet where the polymer melt is formed into the desired shape (Kazmer, 2009).

Rotational molding, another process to manufacture pallets starts by introducing plastic in the form of powder, granulated or viscous liquid into a shell-like mold, which is rotated about two axes perpendicular to each other while is being heated at the same time. This rotational movement and heating cause the material inside the mold to distribute and adhere to the internal configuration of the mold, forming a solid layer. The mold is then cooled as it continues to rotate in order for the material to solidify, defining the desired shape (Crawford & Throne, 2002; LeBlanc & Richardson, 2003).

2.3 Composite Pallets

Various types of composites have also been developed for pallet production that includes primarily plastic and wood composites. Wood flour and wood fiber might be added to certain polymers such as polypropylene and polyolefins to enhance the mechanical performance of the material as a whole (Khoo, Ratnam, Shahnaz, & Khalil, 2008).

However, the most common composite pallets are wood composites in the form of wood particles and plywood. Wood chips and resin at high temperatures, and pressure formed press wood pallets that offer the advantage of nestability (Pearson, 2016). This kind of pallet is not widely used in the industry, with estimates indicating that they are used only by 14% of industrial facilities (Bond, 2018).

Other composite pallets are made using engineered wood like oriented strand boards (OSB) and cross laminated layers, that provides smooth, warp-resistant platforms and greater performance consistency between pallets. As high heat is necessary during their production, OSB pallets are exempted from phytosanitary regulations, being regularly used by export-oriented industries like electronics and pharmaceutical (LeBlanc & Richardson, 2003).

Some of the disadvantages present in wood composite panels include a higher cost than solid wood, expensive repair, less weather resistance and the requirement for fasteners (Clarke, 2003). Although fasteners are still present in wood composite pallets, the nail protrusions are eliminated and the amount needed is less than in solid wood pallets (LeBlanc & Richardson, 2003). Industrial applications for this type of pallet include pest sensitive product transportation, exports and imports (Montoya, 2017).

2.4 Paper-Based Pallets

Although during the period between world war I and world war II, the container applications shifted from wood to corrugated, pallets were not part of that change. Although paper-based pallets are more expensive than solid wood pallets, the opposite is true for boxes (Clarke, 2003). Advantages of paper-based pallets include light weight, cleanliness, and absence of phytosanitary issues (LeBlanc & Richardson, 2003). Nonetheless, they also present important disadvantages like their susceptibility to moisture, the lack of stiffness, low durability and low product protection (Clarke, 2003). In spite of these concerns, corrugated pallets still are able to find a niche market with 4% of industries employing them in their operations according to estimates (Bond, 2018). Industrial application for this type of pallet include air freight transportation, and other weight sensitive applications (Montoya, 2017).

2.5 Metal Pallets

Heavy duty operations that require outstanding performance usually use metal pallets (Freedonia Group, 2015), although they make up less than 1% of the market (Clarke, 2003), and are used by 6% of industrial facilities (Bond, 2018). Carbon steel, aluminum and stainless steel are commonly the metals used for pallet production, which can cost up to more than three times the price of solid wood units. Generally employed in closed loop environments, great strength, stiffness, durability, product protection and excellent sanitary performance account as positive aspects, while their initial high price, weight, low friction and susceptibility to rusting add to the disadvantages (Clarke, 2003). Automotive, pharmaceutical, tires and heavy duty operations industries are good representatives of metal pallet users (Clarke, 2003; LeBlanc & Richardson, 2003). Table 2 presents a summary of the materials used to manufacture pallets, their advantages, disadvantages, and industrial use.

Table 2. Pallet Materials Summary

Material	Advantages	Disadvantages	Industrial Use
Wood	Low Cost Easy to prototype Recyclable High wood availability Strength Stiffness	Proclivity to harbor insects and fungus. Variable performance. Moisture problems	General industrial use
Plastic	Safety Durability Design Potential Fastener free	High cost Low friction Low stiffness	Automotive Pharmaceutical Dairy Beverages High sanitation requirements
Metal	Strength Durability Sanitary performance	High cost Weight Low friction Susceptibility to rusting	Automotive Pharmaceutical Tires Heavy-duty
Composites	Nestability Performance consistency No phytosanitary issues	High cost Less weather resistant	Pest sensitive industries Import and export operations
Paper based	Light-wight No phytosanitary issues	Susceptibility to moisture Low stiffness Low durability Low product protection	Air freight Weight sensitive applications

3. Wood Pallet Design

There are multiple software platforms that help professionals in the supply chain industry to better design pallets based on the demands of their production lines, distribution channels, storage and retail conditions (Modern Materials Handling, 2012). Some of the software tools used for pallet design include the Pallet Design System, developed by the National Wooden Pallet and Container Association(National Wooden Pallet and Container Association, 2018);

Best Pallet, developed by White & Company (White & Company Packaging Solutions, 2011); Cast a Pallet 3D, developed by Italian firm Gruppo 36srl (CaP3D, 2018); Quick Pallet Maker, developed by US-based software company Koona (Koona LLC, 2018); PalDraw, developed by Automated Machine Systems, which provides automated equipment, software and design services for material handling (Automated Machine Systems, 2018).These tools function in similar ways, as all of them require specific inputs regarding sizes, classes of pallets and other specifications and provide specific drawings and information useful to the users and the manufacturer. However, the detailed technical differences between them are not subject of research in this work.

When designing a pallet with the Pallet Design System (PDS), for instance, the tool will require the user to provide information regarding the pallet type, size and style, dimensions for every component. The user also has plenty of options to select regarding the kind of material used in the pallet like plywood, oriented strand board and wood species. Other features like the kind of fasteners and its specifications, chamfers, clipped corners, strapping notches and slots as wells as the pallet treatments can be specified (National Wooden Pallet and Container Association, 2018) .

The PDS creates a detailed sheet that includes top, bottom, side and end views as wells as 3-D drawings. If required, the software also provides a pallet production order for manufacturing. The software is also capable of executing engineering analyses to predict performance of the pallet according to the load used in handling and storage. Several options for unit load configuration are also available (National Wooden Pallet and Container Association, 2018).

4. Pallet Testing

Testing on pallets has the purpose of evaluate new designs and materials for new pallets, compare to other existing or competing pallets or to assess if a pallet's performance will be sufficient to be employed through the different stages of a company's specific supply chain (Nelson Company, 2014).

Pallet testing aims to measure three fundamental parameters, which are strength, durability, and functionality. The strength of the pallet and its stiffness determines the maximum load capacity for the pallet under different conditions like static compression, where the pallet holds the load while being fully supported, like laying on a flat warehouse floor. Dynamic compression is another condition that a pallet can experience, for example in a truck trailer, where the vibration adds additional load strains. When the pallet is not fully supported like in a conveyor system or a warehouse storage rack, then the pallet is subject of racked compression. A forklift lifting a pallet with load on top is another example for load conditions where the pallet is not fully supported (Nelson Company, 2014).

As the pallet interacts with different handling systems through the supply chain like conveyors and forklifts, it is important to make sure that the pallet will be durable enough to withstand the environment conditions, especially if the pallet has been designed for multiple uses.(Nelson Company, 2014).

Lastly, but not less important, it is necessary to guarantee that the pallet with be compatible with the handling equipment through the supply chain and meet regulations regarding aspects like pest control, heat treatments and fire safety. Tests are done usually following accepted standards created by organizations like the International Standard Organization (ISO), the International Safe Transit Association (ISTA) and the American Society for Testing and Materials, although testing might be customized as well (Nelson Company, 2014).

5. Pallet Management Systems

It is important for every company to establish a policy regarding the use and management of pallets through its supply chain that considers supplier and customer issues, regulatory aspects and corporate strategy, with the goal of reducing logistics costs and adding value to the organization (LeBlanc & Richardson, 2003). Factors like the configuration of the supply chain, the type of product, and others influence the choice of pallet management strategy (Carrano et al., 2015).

The pallet logistics design problem is an important subject of research, as they represent critical assets for a business' cost and functioning optimization (Elia & Gnoni, 2015). Three predominant strategies are widely used in the industry for pallet management: single-use approach, also called open-system, re-usable approach, also called closed-system, and reusable leased pool approach, in which the pallets are not purchased by the producing company, but rented from a pallet pooler that manages a reusable stock of pallets (Carrano et al., 2015).

With the single-use expendable approach, also known as open-loop approach or open logistic network, the pallet is not expected to come back once it has been delivered with products to a customer, as the ownership of the pallet is transferred with the load (Carrano et al., 2015). Inexpensive wood is often used for this kind of strategy, which results in low price for the pallets (Roy, Carrano, Pazour, & Gupta, 2016). The open-loop systems are simpler, but require the design of empty pallets inventory management system that accounts for warehouse capacity and replenishment models (Elia & Gnoni, 2015).

With the closed-system, pallets can be interchanged either directly or indirectly. In the case of direct interchange, the carrier collects the empty pallets in the same trip used to transport the products to the customer, which means that the carrier must wait until the palletized product is unloaded, except if the customer has enough amount of the same type of pallets, so the carrier just needs to make sure that the quality is satisfactory before being able to take them back to the company. Another way of avoiding waiting times when delivering palletized unit loads in the closed logistic network, is to apply an indirect or postponed interchange approach for pallets, in which the customer releases a voucher that specifies the quality and amount of delivered pallets, and commits to physically give back the same amount, quality and type of pallets in a given period of time. In this case, it is important for the company to define a reasonable delay time, as the lack of physical return of pallets might produce availability shortage (Elia & Gnoni, 2015).

The third system, re-usable leased pool is a system in which the producing company does not purchase the pallet, but rather rents it from a pallet pooler that manages a circulating stock of pallets. In this system, once the product reaches the customer downstream the supply chain, the pallets are put aside to be picked up by the pallet pooler, who takes care of repairing, re-allocating, recycling, and disposing (Chen, Ren, & A, 2019).

B. THE SUPPLY CHAIN

The supply chain concept is defined by Russell (2007), as “the sequentially-connected organizations and activities involved in creating and making a product available”, a process that goes from the very point of origin of raw materials in nature until the final customer that consumes a product. Supply chains are composed of multiple entities that transcend the boundaries of the company to include not only its own nodes in the supply chain network, like manufacturing plants, warehouses, and distribution centers, but also those of its suppliers and its customers (Rivera, Wan, Chen, & Lee, 2007; Simchi-Levi, Kaminsky, Simchi-Levi, & Shankar, 2016).

According to Russell (2007), the supply chain encompasses more than logistics, and implies a change in business philosophy that moves away from a make-to-stock production paradigm towards a customer driven demand strategy. This change requires seamless information flow between echelons in the supply chain, reason for which key alliances are the core of the supply chain and information systems work to keep the chain together (Russell, 2007). Figure 4 shows the relationship between the internal processes of the company that are related to the supply chain functions, like product manufacturing, sourcing, and distribution.

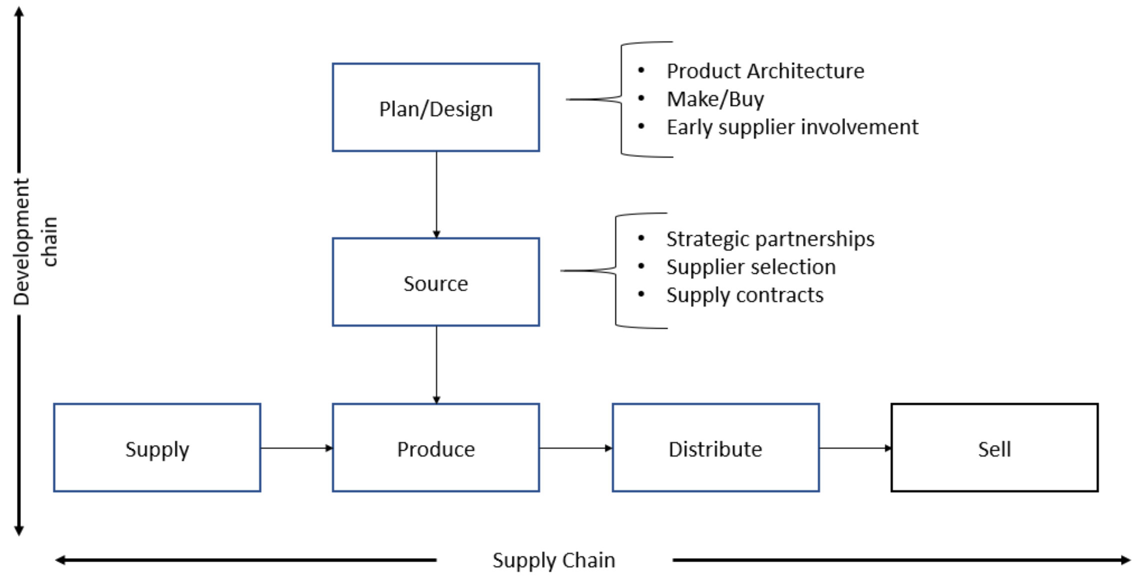

Figure 4. The Enterprise Development and Supply Chain Model (Simchi-Levi et al., 2016).

1. Supplier and Customer Relationships

A close collaboration with other enterprises to achieve a more integrated supply chain is aligned with the main purpose of a company, which is the generation of financial profits. The establishment of relationships with other companies based on common goals contributes to the company's focus of understanding the requirements for customer satisfaction, hence ensuring business continuity (Rivera et al., 2007).

A framework for to approach the management of supplier relationships was developed by Park, Shin, Chang, & Park (2010), which is presented in Figure 5. The first module of the framework deals with shaping the purchasing strategy of the company considering factors like product criticality, relationship with the supplier, and supply risk. The second module of the framework is supplier selection, which relates to the processes that a company uses to select its suppliers based on factors of interest for the company, like cost, quality, and delivery. The third module is supplier involvement, which the authors divide into production operations, dealing with exchange of information that allows better scheduling in manufacturing, and product development, which involves the suppliers when the company is developing a new product to reduce time-to-market and make sure that the product is feasible from the raw material supply stand point. These points are also elaborated by Russell (2007), and by (Ferrara, 2013).

The fourth module is supplier assessment and development, which consists of an assessment with the purpose of determining the strategic importance of supply materials, evaluating supplier performance, determining the status of the relationship with each supplier. Lastly, the fifth module relates to strategies based on Plan-Do-Check-Act cycles to improve the supplier relationships in the company.

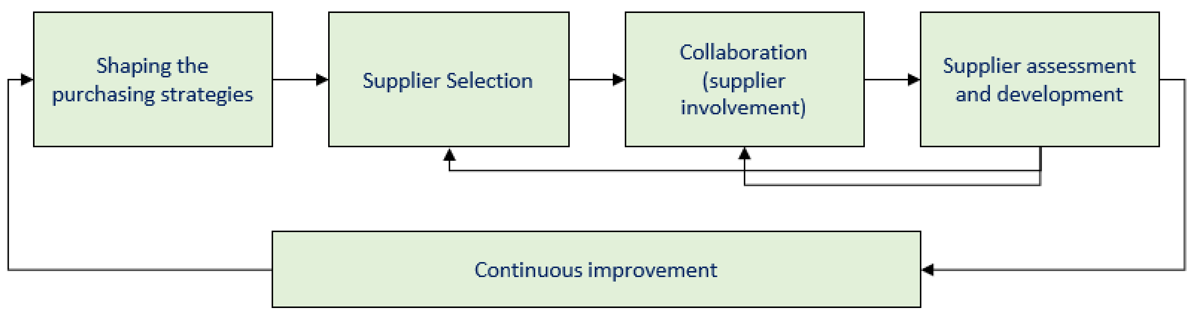

Figure 5. Integrative Framework for Supplier Relationship Management (Park et al., 2010).

Customer relationships management are also essential for communication in the supply chain (Russell, 2007). Given that customers know best what they value about the company's products, and possess more information about their business needs, involving the customers in the product development process is a good way for companies to innovate and create new products that are more likely to be profitable in a sustained manner (Ferrara, 2013).

From an operational standpoint, communication with customers is also necessary to better coordinate manufacturing scheduling and forecast future demand, which allows for more efficient inventory management (Russell, 2007).

2. Transportation

In the context of supply chain, transportation is a function encompassing infrastructure, equipment and processes that enables the movement of goods necessary to provide customers with products and services (Geunes & Taaffe, 2008).

3. Warehousing Operations

The role of warehousing operations in the supply chain is to provide the utility of time and place for a company's customers by filling the gap between current demand and current production (Sharp, 2008).

4. Packaging

The concept of packaging is defined by Bjärnemo, Jönson & Johnsson (2000) as cited by (Saghir, 2002), as "a means of ensuring safe and efficient delivery of goods in a sound condition to the ultimate customer, supplemented by efficient re-use of the packaging or recovery and/or disposal of the packaging material at minimum cost". This definition is more related to the role that packaging has from a product distribution point of view. Other approached to packaging consider its role from a marketing point of view, as packaging can also be used to identify the product, provide information, and look appealing to the customer so that the product is purchased (Stock, 2008).

There are three categories for packaging: first, the primary package, which is in direct contact with the product, and whose purpose is to contain the product and display useful information to the customer. The secondary package, which usually envelops, or hold together a group of primary packaged items. The tertiary package is the container that is used for storing and shipping purposes (Stock, 2008).

Distribution packaging has a significant impact in the efficiency and cost of logistic activities related to product distribution and customer service (Stock, 2008). Understanding the distribution environment in critical phases like transportation and warehousing, and using this information to drive the packaging design has some advantages, as mentioned by Stock (2008):

- Lighter packaging that translates in less fuel consumption
- Better warehouse and transportation space utilization
- Stronger packaging that reduces product damage

5. Supply Chain Challenges Related to Distribution and Logistics.

The distribution processes of the supply chain involve the physical movement of products from one place to another. For instance, from suppliers to manufacturing facilities, to warehouses, distribution centers and customers. Over the last thirty years, supply chains have become more internationally oriented as a result of globalization, causing an increase in the complexity of distribution operations, and creating new challenges to guarantee the integrity and quality of the products across all the stages of the supply chain (Skorna & Fleisch, 2012).

One of the risks affecting the distribution of goods during transportation is cargo theft. Ekwall & Lantz (2015) examined the patterns of reported cargo theft in the European Union, the middle east and Africa and found that approximately 41 percent of crimes take place when the product is moving and 59 percent when the trucks are parked during a stop, a case in which the predominant type of crime is focused on the volume of the cargo rather than its value. The European Parliament estimates that 10.4 billion dollars were lost annually in 2007 (Van den Engel & Prummel, 2007).

Counterfeit is another concern when distributing products, particularly when the number of agents intervening in the supply chain is high and widely distributed (DiMase, Collier, Carlson, Gray, & Linkov, 2016). It is estimated that 36 million counterfeited items were confiscated in the European Union in 2013 and 28000 seizures took place in the United States. The consequences of such phenomena include economic losses, health and safety risks and even national security concerns (DiMase et al., 2016). Azuara, Tornos, & Salazar (2012) and Kwok, Ting, Tsang, & Cheung (2010) proposed a RFID traceability system to improve the detection of counterfeited products in the supply chain, the first being implemented in a case study of a ham production facility in Spain and the second being implemented in a case study of a pharmaceutical company in Hong Kong.

One approach to discover issues taking place in logistic processes of the supply chain is to analyze cargo insurance claims. Skorna & Fleisch (2012), analyzed data corresponding to 4 years of claims, from 2005 to 2008 for one of the largest cargo insurance companies in Switzerland, for a total of 7 284 claims.

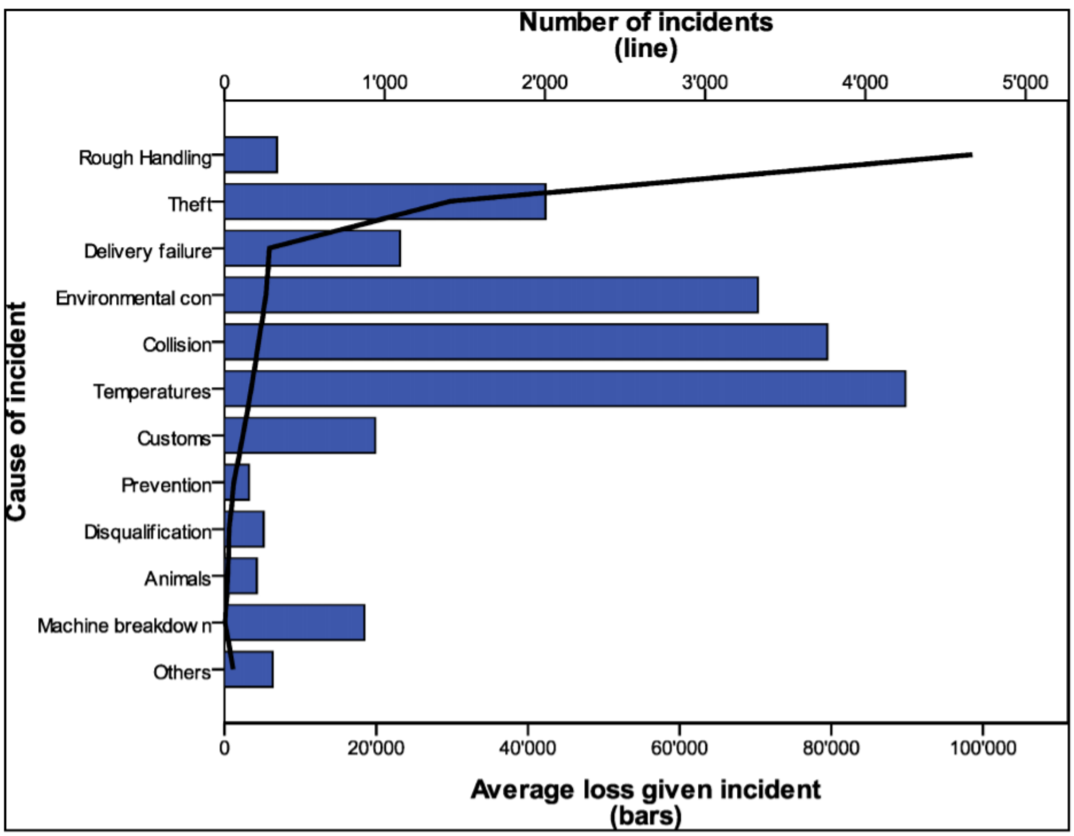

Figure 6. Average Loss per Incident and Number of Incidents by Causes (Skorna & Fleisch, 2012).

Figure 6 shows the summary of the results, where the blue bars represent the average loss generated given an incident and the black line represents the frequency of the incident. The average loss found per incident was $19 265. More than 90% of the claims could be assigned to six causes: rough handling, theft, delivery failures, environmental impact (moisture, oxidation, fire), collisions and temperature. Although 60% of the claims are related with rough handling, only 20% of the claims cost is assigned to rough handling, contrary to temperature, for instance, which shows the highest average loss given incident (Skorna & Fleisch, 2012).

C. INDUSTRIAL INTERNET OF THINGS

More efficient decisions can be made by logistic professionals and supply chain decisionmakers by adopting cyber-physical systems that will allow real time information availability, providing visibility in the supply chain. Cyber-physical systems (CPS) are engineered systems that include physical devices such as advanced sensors, computers and mobile devices as well as software and digital platforms (Barreto, Amaral, & Pereira, 2017). The optimization of a logistic network supported by CPS involves the concept of internet of things (IoT), which consists of the idea that processes and devices can communicate with each other and with humans through connectivity mechanisms imbedded in them, thus enhancing the potential improvements in the supply chain (Barreto et al., 2017).

The internet of things aims the integration of the physical world and computer-based systems by embedding objects with sensors, electronics and software that will exchange collected data with one another using a form of connectivity within a network. The exchange of information in the network of smart objects is mostly carried out using existing internet infrastructure rather than local range intranets. As most of the devices prone to be used as IoT elements are limited in battery capacity, the development of energy-efficient networks is a crucial aspect (Huang & Hua, 2017).

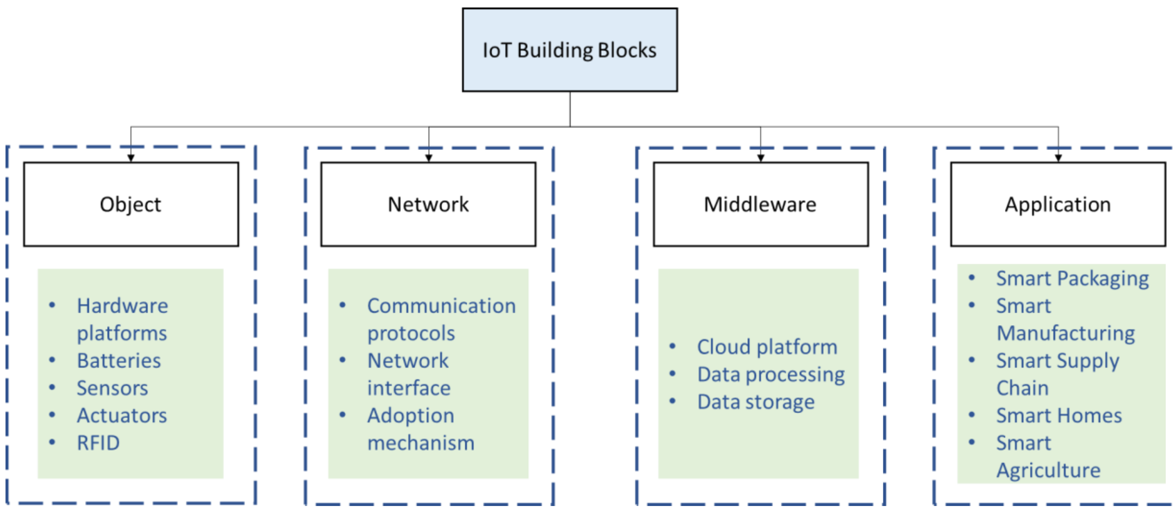

Figure 7. Internet-of-Things Building Block. Adapted from (Colakovi & Hadzialic, 2018).

IoT systems are based on sensors, actuators, controllers and monitoring activities, all devices with the potential of communicating with each other, collect data or process data locally or sending it to a central server or cloud service platform. All IoT devices capture data of interest that when processed with analytics provide useful insight to make better decision and undertake more effective actions (P. P. Ray, 2018).

The structural design of IoT platforms is crucial for a satisfactory performance of the network. One of main concerns that must be considered when designing an IoT network is the limited energy resources available in an IoT context. Energy preservation is important given that sensors have limited battery capacity and having devices running out of energy interrupt the collecting and transmission of information, shutting down critical parts of the IoT network and making it useless. The adoption of the new sensor technologies can reduce this risk. Also, the way the network is design should be focused on minimizing energy consumption. The network should also be designed in a way that minimizes the density of nodes or devices, as well as avoiding other nearby transmitters, reducing the risk of signal interference (Huang & Hua, 2017).

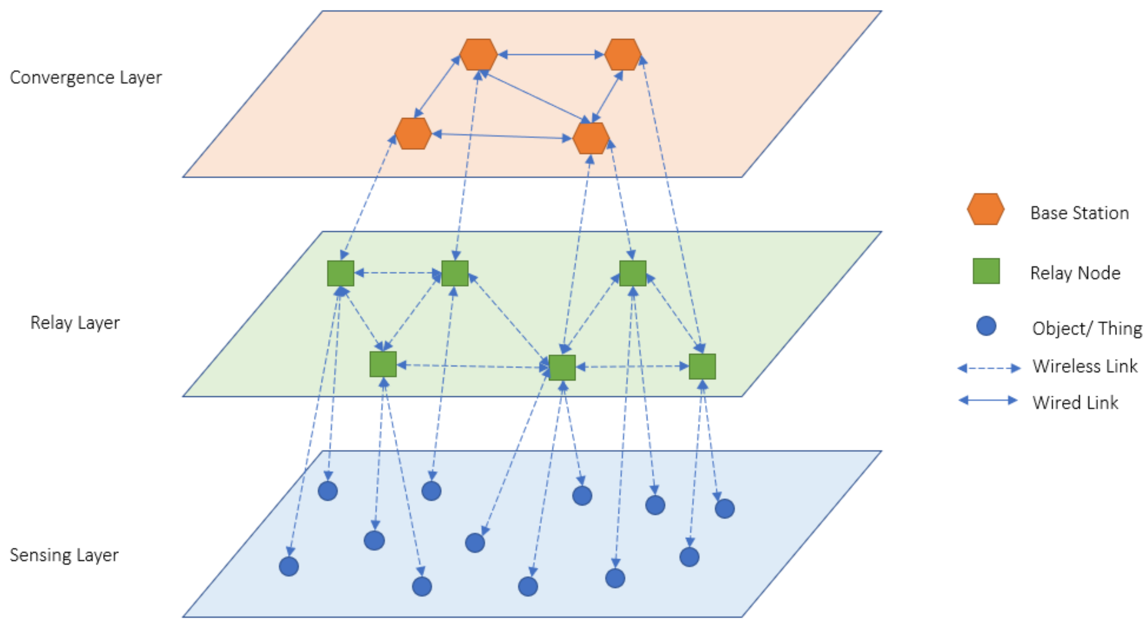

Figure 8. Example of Framework for IoT Network Systems. Adapted from (Huang & Hua, 2017).

Machine-to-machine (M2M) and machine to person communications can be enabled by the internet of things (IoT). It is important to justify every new application developed using this technology with a clear value proposition that benefits all stakeholders involved (Ericsson, 2016).

The means by which proper functionality of the cyber-physical systems that conform IoT occurs is a technology stack made up of several technologies that enables the processes of data collection, communication, and services. The functional blocks that support an IoT system can be categorized into four main domains that include hardware and software. An IoT platform, either hardware or cloud, is what integrates the enabling technologies, connecting the physical and virtual “things” to the network and deriving applications and the development of a certain service (Colakovi & Hadzialic, 2018).

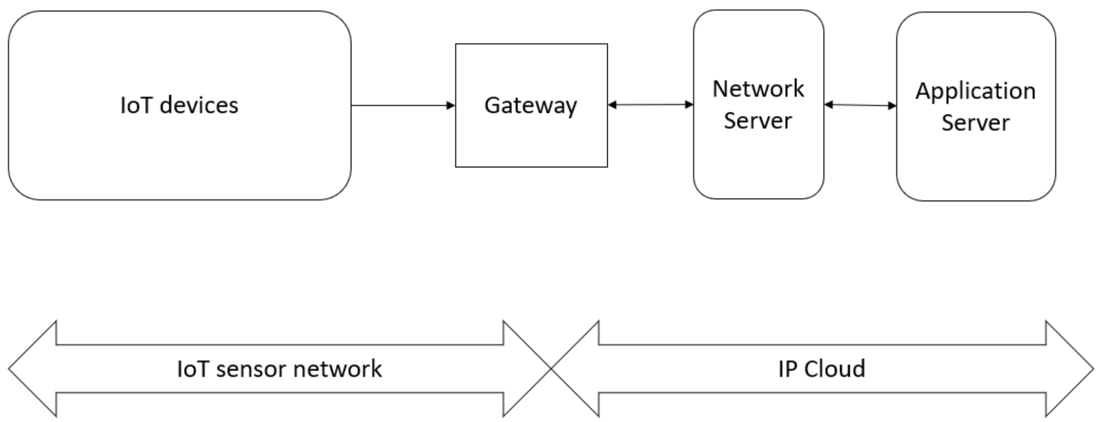

Figure 9.Internet of Things Network Architecture (Kim, Kim, Hassan, & Park, 2017).

Figures 8 and 9 show examples of IoT architecture frameworks, that matches the four domain functioning block classification for the IoT enabling technologies made by Colakovi & Hadzialic (2018) shown in Figure 7.

1. Object layer: Sensor technology

A smart sensor is a device that measures the physical parameters of processes or environments. When incorporated with advanced technologies, like microprocessors and connectivity capabilities, a smart sensor can provide valuable data that triggers analytical processes with the potential of reducing costs, boosting operations productivity, and improving customer satisfaction. However, by themselves, sensors cannot provide end-to-end supply chain visibility. They need an entire cyber-physical-system that involves a means of connectivity and a platform to transmit and process the data collected (Fitzgerald, Mussomeli, Daecher, & Chandramouli, 2018). A wireless sensor node (WSN) is made up of a processing module, a low-power micro controller unit (MCU), sensor modules and a radio frequency communication module that work with a certain kind of wireless communication technology (Tzounis, Katsoulas, Bartzanas, & Kittas, 2017).

There are a wide variety of sensors in the marketplace that can be deployed as part of an IoT network. Depending on the specific requirements and nature of the processes and the applications, they can be used to monitor and control manufacturing, transportation, and other types of conditions in real time. For tracking and supply chain management, some smart sensors utilize novel cellular technologies like LTE-M and NB-IoT. Also, short-range technologies like Bluetooth 5 have been developed (BeWhere Inc, 2018b) .The following is an overview of the multiple options available.

1.1 Temperature/ Relative Humidity

These sensors are designed to be employed primarily in applications like air conditioning, refrigerators, smart homes, industrial automation, air humidifiers and assets and goods tracking. Many of these sensors can work in rough environments, from -40 °C to 120 °C. Some of the sensors available in the market like HTS 221 developed d by STMicroelectronics®, only provide a digital signal of the value measured, but their data can be accessed through I2C/SPI interface, which is a way of communication between circuits

(STMicroelectronics, 2016). This enables the sensor to be integrated with a wireless technology microcontroller, which will be the entity in charge of communicating the information from the sensor to a gateway or directly to the cloud, depending on the application.

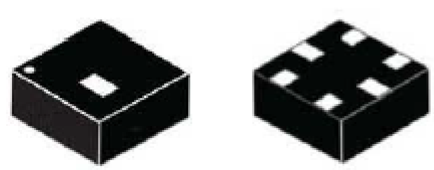

Figure 10. Representation of the Temperature and Relative Humidity Sensor ST HTS221. (STMicroelectronics, 2016).

Other sensors incorporate the technology for communication within the sensor, as is the case, for example, with the ALTA wireless temperature and humidity sensors manufactured by Monnit® providing 100 ft of range coverage. These are also equipped with a Lithium battery that is specified to last up to 10 years. The device also has the storage capacity to record and store up to 512 incidents of sensed data in case communication with the gateway/cloud is interrupted. An important feature of sensors like those offered by Monnit ® is that they are programmed to sleep for a given amount of time, what is known as a heartbeat, and then send the signal with the sensed temperature; therefore, optimizing energy consumption.

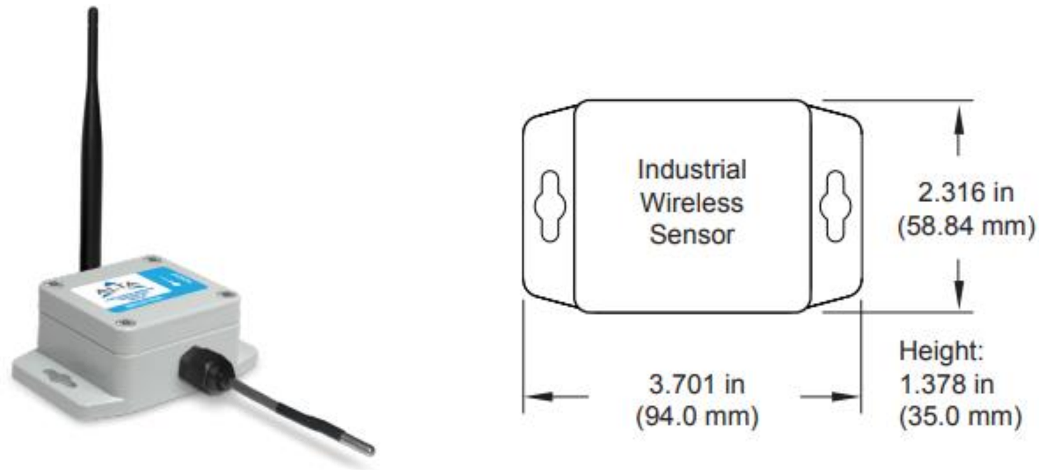

Figure 11. Example of Industrial Wireless Sensor for Temperature (Monnit, 2020).

Electronic component companies like TE Technologies provides seven different types of temperature sensors with I2C/SPI capabilities that can be used for IoT applications. Multiple integrated options are offered for sensing temperature and humidity by Texas Instruments, providing high accuracy levels of +-0.2 °C and offer 10-year battery life using lithium coin cell batteries. This model is equipped with an ultra-low power wireless MCU (microcontroller unit) that has the advantage of being able to work with several platforms like Bluetooth®, ZigBee®,6LoWPAN, and ZigBee RF4CE.

1.2 Vibration

Most accelerometers are able to measure vibrations in real time and give an alert when the sensor experiences a force beyond a specified value. For transportation applications, however, the interest is not always in a particular event, but rather the continuous conditions experienced by the products during transit. Knowing these continuous conditions is needed, so that such conditions can be recreated for product testing, improvement, and damage prevention. Lansmont offers a solution that provides this information and is called the SAVER 3X90. This device has battery power lasting for 90 days of continuous operation, which makes it suitable for being deployed in a trailer that will follow a specific route of interest so that a vibration profile for that route can be captured. The data is then exported to a software and the vibration conditions can be recreated for testing purposes. The disadvantage in this case is that the device does not transmit data in real time, but it has to be transferred to a central storage afterwards.

Figure 12. SAVER 3X90 Field Data Recorder (Lansmont Inc, 2018).

1.3 Pressure

TE technologies offers multiple sensors with digital output. The only device that is offered as an integrating solution with communication capabilities is the wireless pressure transducer that uses Bluetooth® 4.0 wireless connection as its method for communication.

It has been conceived as a device for multiple applications such as industrial control, off-road vehicles, refrigeration systems, pumps, compressors, agricultural equipment, and others. It provides +-0.25% accuracy and is able to work from 0-50 psi to 15000 psi with a 2-year battery life.

Figure 13. Wireless Pressure Transducer (TE connectvity, 2020).

1.4 Integrated Solutions

BeWhere Inc is a company that offers LTE-M devices capable of providing full tracking information; their devices both sense and transmit collected data of temperature, relative humidity, barometric pressure, light exposure, location, motion, and impact. These devices are equipped with long-life ACC batteries, providing up to 8 years of battery life (BeWhere Inc, 2018b).

Figure 14. BeWhere-MIoT Tracking Solution (BeWhere Inc, 2018b).

Other sensors use Bluetooth technology for transmitting their data instead of cellular networks. The BTB-04, manufactured by BeWhere Inc, is an example of this technology. Using BLE, this sensor is said to able to send data up to 250 meters; data consisting of measurements of temperature and impact counts, obtained by measuring how many times the device experiences an acceleration exceeding a certain threshold (BeWhere Inc, 2018a).

Figure 15. BTB-04 Smart Beacon(BeWhere Inc, 2018a).

Figure 16. Smart Sensor XT 4970 Developed by Xirgo Technologies and Offered by AT&T for Tracking Applications (Xirgo Technologies Inc, 2018).

AT&T offers tracking solutions for supply chain applications by means of small, lightweight sensors with robust capabilities such as providing GPS location and readings of humidity, motion, temperature, shock, pressure, light and vibration (AT&T, 2018). AT&T also offers complete solutions ready to be installed and deployed; sensors for which a software platform to access the data transmitted is already incorporated. This all-in-one type of sensor aims to reduce the cost of creating IoT solutions from scratch.

Sonim XPi is an example of a smart sensor powered by Intel LTE that uses the LTE network for which AT&T offers a monthly subscription plan to collect the data from the sensor. Its rugged design functions in extreme weather conditions. This is a feature that, along with the previously mentioned features, make this device a good option for high-value assets tracking (AT&T, 2018).

Figure 17. Sonim XPi Smart Sensor (AT&T, 2018).

Another solution by which to monitor supply chain conditions is the SAVER AM Asset Monitor. This device is capable of measuring acceleration, temperature, relative humidity, atmospheric pressure, tilt, and light. This option, however, requires an external power to extend its running time, and it uses an USB connection for communication, instead of wireless connectivity, so the data is not collected in real time (Lansmont Inc, 2018).

Figure 18. SAVER AM Asset Monitor(Lansmont Inc, 2018).

2. Network Layer: Communication Technology.

The foundation of IoT and tracking applications in general is connectivity. There are several ways in which connectivity can be achieved depending on the needs and nature of the application. Some applications might require short-range connectivity, and they employ radio technologies like Bluetooth and Wi-fi. Other applications requiring long-range connectivity can use 3GPP (third generation partnership project) cellular network technologies like GSM (global system for mobile communication), WCDMA (wideband-code division multiple access), LTE(Long term evolution) and in the coming future 5G(fifth generation wireless systems) often known as wide-area networks or WAN’s (Ericsson, 2016).

2.1 Wireless Personal Area Networks (WPAN)

2.1.1 Bluetooth

Bluetooth is a communication standard that enables the wireless transmission of data using radio transmission waves at high speeds. The range of functioning goes from 1 m to 100 m, depending on several technical parameters. Bluetooth Low Energy (BLE) was introduced for the first time in 2013, and has been renowned for its energy efficiency, which enables it to be applied in novel applications like IoT (Diaz & Wang, 2016).

Bluetooth 5, the newest version of this technology incorporates new advancements that promise to further fit a broader range of IoT scenarios. The new version has increased range capacity, and transmission speed from 1 mbps (megabyte per second) to 2 mbps without increasing energy consumption. Messaging capacity has increased 800% compared with the previous versions. Interoperability with other devices is achieved by a large number of devices already using the technology; an estimated 96% of all the tablets and smartphones produced use Bluetooth technology (Bluetooth SIG, 2017).

Bluetooth mesh is the new network topology developed by Bluetooth SIG specifically designed to address the needs and challenges of IoT. It aims to create a reliable, industrial-grid device network. One of the advantages of the Bluetooth mesh network technology is that its many-to-many topology enables the communication of any device (also called Bluetooth beacon) with any other device that is part of the mesh. This extends the range of communication far beyond the radio range of an individual node (Wolley, 2017).

It is important to note that communication in a mesh network is message oriented and is classified into two categories: acknowledged and unacknowledged. Acknowledged messages require a response from the receiving node that confirms the message was received and returns any data that might have been requested to the original sender; whereas, an unacknowledged message is a one way communication (Wolley, 2017) .

2.1.2 ZigBee

Zigbee is a wireless personal area network based on the IEEE 802.15.4 standard that provides low-cost and low-power consumption wireless communication. Zigbee operates in two separate frequency ranges, 868/915 MHz for regional cases in Europe and the Americas, respectively, and 2.4 MHz on a global scale. Medical sensor applications, industrial controls, consumer electronics, and smart home devices are the main targets for the adoption of this Zigbee technology as a way of communication (Zigbee Alliance, 2018).

The two most recent specifications include the option for network topology, making possible the inclusion of up to 65 000 devices as part of a Zigbee deployed network. The range of communication goes from 75-100 m for indoor applications to more than 300 m when there is an open line of sight. As for raw data throughput, 10kbs are achieved at 915-921 MHz, 100 kbs at 868 MHz and 250 kbs at 2.4 GHz (Zigbee Alliance, 2018).

2.2 Wireless Local Area Network

2.2.1 Wi-Fi

Wi-fi, the abbreviation of wireless fidelity, is a wireless connectivity technology that aims to improve the functionality of wireless local area networks (WLAN) (Pistotia, 2009). A significant limitation of this technology is, by definition, its limited area of coverage (Guillemette, 2018), which goes typically to 50 m, with a data rate of 9.6 Gigabytes per second (Meller, Ward, & Gesing, 2020). However, it is a ubiquitous connectivity technology that is already widely used by a vast number of devices. Estimates indicate that 500 million wi-fi enabled devices will be shipped by 2021, of which approximately 62% will be smart home related items (Rama, 2017).

Originally, wi-fi technology was created focusing on short-range applications, cross-vendor interoperability, and for use in desktop devices for which energy efficiency concerns were not crucial. These features make wi-fi an excellent technology for in-building applications, as coverage has become omnipresent in our environment; however, it might not be appropriate for every application that requires connected devices (Parekh, 2017).

There are limitations in wi-fi technology that hinder its implementation in IoT applications, which has led the IEEE (Institute of Electrical and Electronic Engineers) to publish two new standard specifications: 802.11ah and 802.11ax. Range and power concerns were the focus of Wi-Fi HaLow, the technology now using the 802.11ah standard. Although energy consumption and range capacity were improved, there has not been a widespread adoption of the technology by chip manufacturers (Parekh, 2017).

The 802.11ax standard introduced a new technology called “multiple-input multiple-output – orthogonal frequency division multiplexing” (MIMO-OFDM), which increased the throughput and subdivide signals. The results of this were particularly helpful in high-density environments, which was one of the major setbacks to current wi-fi technologies. These new standards give a better prospect for wi-fi’s implementation in IoT applications.

2.3 Wireless Wide Area Networks.

2.3.1 LoRa

Low-power wide area networks are being implemented as new applications requiring wide range coverage and low power consumptions have emerged. The technology is particularly useful for systems that need to send and receive low amounts of data within a range of up to 50 Km (Lin, Shen, Miao, & Liu, 2016; Meller et al., 2020).

When the LoRaWAN topology is deployed, a gateway relays messages between end devices. This gateway has the capability of bi-directional communication: to the end devices and to a central network server. It also has a data rate that varies from 0.3 kbps to 50 kbps (LoRa Alliance, 2018). LoRa works in a non-licensed band below 1GHz. Its underlaying technology was developed in the 1940’s and has been used in military applications due to its long range capabilities; however, LoRa is the first implementation of this technology for commercial purposes (Sharan Sinha, Wei, & Hwang, 2017).

LoRaWAN uses unlicensed bands, 867-869 MHz in Europe, 902-928 MHz in North America and 433 MHz in Asia. Although the environment and obstructions in a given location directly influences the range capacity, a single gateway can cover hundreds of square kilometers, and even entire cities (LoRaAlliance, 2015) with a battery life of up to 10 years per device (Sharan Sinha et al., 2017).

Three categories of LoRa device have been defined depending on the specific requirements concerning the communication latency and battery life. Class A devices are battery powered sensors that are energy efficient and supported by all devices. Class A devices communicates with servers only during certain predefined windows of time. Class B devices are battery powered actuators for which extra windows have been scheduled for communication with the server. Class C devices are powered actuators that communicate continuously (LoRaAlliance, 2015).

2.3.2 SigFox

SigFox is another low-power wide-area network that functions using unlicensed band of 200 kHz and an ultra-narrow bandwidth of 100 Hz wide. This narrow band allows the technology to be deployed in a very efficient way with low noise and interference levels; therefore, saving power consumption. However, such advantages come with the price of having a low throughput of only 100-600 bps (Mekki, Bajic, Chaxel, & Meyer, 2017; SigFox, 2018), and range of up to 50 Km (Meller et al., 2020).

The Sigfox protocol was designed for small messages with the idea that the fewer bits of data to be sent would mean less power needed resulting in longer battery life. Bidirectional communication between the device and the server is allowed, although with some important restrictions. The uplink communications, meaning the communication from the end device to the gateway or server, is restricted to 140 messages per day and each message cannot be greater than 12 bytes. On the other side, the downlink messages are restricted to 4 per day and cannot exceed 8 bytes in payload length (Mekki et al., 2017).

Although these operation conditions might look significantly restricted, SigFox states that a 12 bytes object can represent for instance 2 GPS coordinates down to 3 meters precision, 6 lab thermometer's reports within a -100 ° to 200 ° with a 0.004° precision, 12 reports of speed up to 255 km/h, 96 switch reports like set to day/night, hot/cold, on/off, or a message of 0 bytes could also be an option when the message itself is the communication. All this is with the aim of maximizing the battery life of the device (SigFox, 2018).

2.4 Cellular Networks.

Cellular technologies can provide connectivity in a wide variety of IoT applications. One of the most visible advantages of the adoption of cellular networks to allow communication in IoT, particularly in massive IoT applications, such as tracking, is its wide coverage around the world. According to estimates, around 95% of the global population are covered by GSM cellular networks and 75% will be covered with LTE networks by 2021 (Ericsson, 2016)

As cellular networks have been designed to handle massive volumes of mobile traffic of data, the transmission of information required by IoT applications can be absorbed by the networks without problem and the use of licensed spectrums guarantee predictable and controlled interference(Ericsson, 2016)

Lowering the costs of the devices by reducing peak rates, memory requirements, and using a narrow band are the improvements implemented by 3GPP (Third generation partnership project, an association of telecommunication standard organizations) to address the challenges posed by the nature of massive IoT applications like tracking. Increasing the battery life by implementing a power saving mode and a function called "extended discontinuous reception" that allows the device to be connected to the network on as-needed basis is another effort to tackle the challenge of energy efficiency (Ericsson, 2016).

2.4.1 EC-GSM

Extended coverage - global system for mobile communications (EC-GSM) is an evolved version of conventional GSM. EC-GSM is designed for IoT deployments where ubiquitous coverage, low device cost, and energy efficiency are all required (Liberg, Sundberg, Wang, Bergman, & Sachs, 2018a). Since its first implementation in 1991, conventional GSM has become the global cellular technology, and it is expected to reach 95% of the population by 2021 (Ericsson, 2016)

Some considerations were taken to make sure that conventional GSM could be used for massive M2M communications. Considerations like making it possible to operate GSM in tight spectrums of 600 kHz to avoid spectrum usage with other technologies, implementing security features of LTE, ensuring that all the changes implemented are compatible with existing GSM deployments (Liberg et al., 2018a)

The technical objectives of the EC-GSM network are to achieve a data rate of at least 160 bytes per second (bps), a latency service of 10 s, an ultra-low device complexity, a system capacity of 60 000 devices per square kilometer and a battery life of up to 10 years (Liberg, Sundberg, Wang, Bergman, & Sachs, 2018b)

2.4.2 LTE-M

LTE-M is an evolved version of LTE designed to make LTE technology attractive for IoT applications. Capabilities for LTE-M for data rates are 375 Kilobytes per second with a range of up to 100 Km (Meller et al., 2020). LTE-M represents the broadest range of cellular IoT capabilities that also include a power-saving mode and extended discontinuous reception in order to address energy challenges (Ericsson, 2016).

2.4.3 NB-IoT

NB-IoT is a cellular network technology for massive machine-type communications designed to provide maximum flexibility in deployment with great coverage, long battery lifetime and low cost per device (Liberg et al., 2018b).This technology uses LTE licensed frequency with a bandwidth of 200 kHz, a maximum throughput of 200 kbps, and a coverage rate of 1 km in urban areas and 10 km in rural (Mekki et al., 2017).

The signal processing mechanisms are simplified, so the complexity of the device itself is decreased, thus reducing its cost. The range of coverage is extended trading off the data rate or throughput (Liberg et al., 2018b). It requires regular synchronization regularly, which makes the device consume more energy than similar applications like LoRa. However, these demands cause NB-IoT to provide low latency and high data rate (Sharan Sinha et al., 2017)

NB-IoT has been designed for applications where the focus is on a high quality of service, and where low latency is intended. Latency refers to the time it takes to transmit data from point A to point B (Sharan Sinha et al., 2017). Another advantage of NB-IoT is that it can be integrated to the LTE system, making easier the deployment process (Bao et al., 2018).

2.4.4 5G (Fifth Generation)

5G is the fifth generation of mobile communication networks that promises not only to increase the interconnectivity of people around the world, but also to enhance further the capabilities required to boost massive IoT deployments and applications (Qualcomm, 2018).

Three broad category applications of connected services have been defined for 5G technology. The first is to enhance mobile broadband, which will not only improve smartphone usage, but allow new immersive experiences like virtual reality. The second is mission-critical communication that will enable new services with ultra-reliable and low-latency requirements for applications like remote asset control. The third is the massive deployment of IoT, connecting embedded sensors in a great variety of areas with a low cost (Qualcomm, 2018). In addition, the technology aims to make the most of every band spectrum: low bands are below 1GHz, medium bands exist between 1GHz and 6 GHz, and high bands are above 24 GHz, which are also known as mm waves that have not been exploited before (Qualcomm, 2016).In terms of capabilities, 5G technology has a data rate of 500 Gigabytes per second and a range of up to 500 m (Meller et al., 2020).

According to recent estimates, the implementation of 5G technology in multiple connectivity applications around the world will lead to a value chain that generates $3.5 trillion in output and support 22 million jobs by 2035 (Campbell et al., 2017).

2.5 Other Radio Technologies.

2.5.1 Radio Frequency Identification (RFID).

Radio frequency identification is a technology that allows automatic transmission of data using radio waves at several frequencies. RFID uses tags, which are miniature chips that consist of a processor into which data is transmitted (Skowron-Grabowska & Szczepanik, 2017). Most RFID applications use passive transponders or tags. These tags do not have a power source in them, but rather receive energy from a reader. The reader emits an electromagnetic wave with a given frequency and constant amplitude to the transponder. This transponder/tag then uses the wave as both energy and as support to send information about the target. The reader then decodes the information and sends it to the database (Duroc & Tedjini, 2018). Some applications utilize tags with their own battery source, especially for long distance reading requirements (Harris, Worrell, Ferrer, & Petross, 2008). In terms of capabilities, Meller et al.(2020) show that RFID can transmit information up to 100 m with a data rate of 640 Kilobytes per second.

According to Harris et al.(2008), the advantages of the radio frequency identification technology include:

- Wireless transmission of data, as no contact between tag and reader is needed.
- No line-of-sight is required, which is opposite of bar code technology.
- Tags can be designed to exist in tough operational environments.
- High store capacity of data, going from 1 bite to several kilobytes (Sen, Sen, & Das, 2009)

According to Harris et al.(2008), the disadvantages of the radio frequency identification technology include:

- Performance problems might occur with certain types of packaging materials that absorb the waves, distorting communication between the reader and tags.
- There are limitations regarding the depth to which RF energy can penetrate.

3. Middleware Layer: Software Platforms.

The vast amount of data that is provided by an IoT network must be supported by middleware platforms that perform storage of information and data analytics tasks. These platforms serve as a means to connect the object layer and application layer within the IoT network. They display the information and data collected by objects to the application's users in a way that provides insightful visualization. This cloud integration is also known as the "Cloud of Things," which delivers, manages, and analyzes data. It also monitors and sends commands to the object layer (Jayaraman et al., 2017); it conveys new challenges like security, resource constraints and scalability. And it offers new opportunities, including: big data processing, new revenue streams, improved customer experience and product innovation (Farahzadi, Shams, Rezazadeh, & Farahbakhsh, 2018).

There are multiple areas and industries for which cloud platforms have been developed. Some of them include: smart agriculture, smart cities, smart homes, car parking, smart buildings, healthcare, sensor networks (Farahzadi et al., 2018), and logistics and supply chain applications (AT&T, 2017a).

An IoT platform or cloud platform is defined as an array of software components that allow connection and exchange of information between IoT devices and applications. The most important requirements to be met by a cloud- internet of things platform are solidness, scalability, adaptability and enhancement of capacity (AT&T, 2017b).

There are multiple providers offering solutions for IoT networks, objects management, and integration, like Amazon Web services, Google cloud, Microsoft Azure, IBM Watson IoT, Xively, C2M, Exosite and others. Microsoft Azure and IBM Watson also provide solutions with artificial intelligence capabilities which are able to solve problems in the objects themselves, for case when information is hard to get into the cloud (Microsoft, 2018). Artificial intelligence is defined as a method that aims to simulate human cognitive capabilities that involve the disciplines of computer science, information theory, neurophysiology, linguistics and cybernetics (Salehi & Burgueño, 2018).

Cloud computing solutions are classified into three major groups: public, private and hybrid. Public solutions are categorized in three ways. First, software as a service (SaaS), in which the application is hosted on one or more data centers belonging to a software vendor or hosted in one or more data centers belonging to an infrastructure as a service vendor like Amazon. Next, infrastructure as a service takes the form of storage and computing services, which are charged to the customer on usage basis. Finally, the platform as a service format provides the complete platform solution. This includes the application design, development, testing, deployment, application services such as data integration and security. Private computing, on the other hand, arose from companies' concerns about security and confidentiality issues. This involves the implementation of the same techniques and technologies associated with public solutions, but kept private by the company and not stored in a public cloud/platform. Lastly, hybrid solutions constitute a combination of these two approaches (Behmann & Wu, 2015).

4. Application Layer: Examples in Supply Chain and Logistics

This section presents some examples found in the literature about the application of Internet-of-Things technology in supply chain scenarios. Yan et al.(2014) developed a system based on the concept of internet of things for supply chain integration and management. The proposed system's architecture was composed of three layers, supply chain process perception that aims to capture information about different segments of the chain, network access convergence to identify the mechanisms to transmit the information perceived in the supply chain that depend on the requirements imposed by the type of application and working environment. The third layer is the supply chain service management platform, that is conceived to manage all the supply chain activities captured by the first layer and transmitted with the second layer. Figure 19 shows the general model that represent the supply chain integration and management with IoT, as developed by Yan et al. (2014)

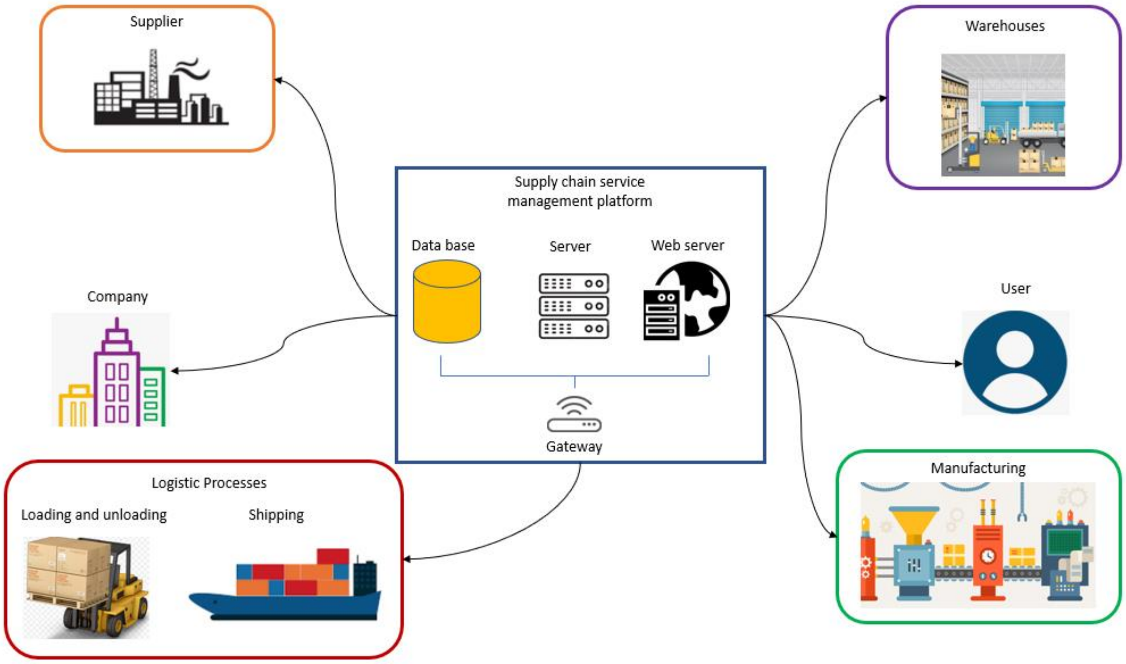

Figure 19. Model for Supply Chain Integration and Management with IoT. Adapted from (Yan et al., 2014).

An intelligent tracking system for the cold chain is proposed by Luo et al. (2016), based on a wireless sensor network built on Zigbee as its protocol for sensor communication within the IoT network and 2G,3G and 4G to transfer the information to monitoring servers. The sensors for this research were placed in storage warehouses and refrigerated trucks that collected temperature data and emitted alerts when critical parameters become abnormal, aiming to have better control over the products and notify on site personnel to take action (Luo et al., 2016).

A supply chain mapping and real-time shelf-life prediction application is found in Jadermann, Praeger, & Lang .(2017). The temperature during transportation for bananas was tracked from Costa Rica to Germany by placing wireless sensors in the center of selected boxes, allowing for more precise shelf life estimation of the product and to identify the "hot-spots" along the chain where conditions were more prompt to cause damage to cargo.

Product identification is a daily activity carried out in warehouses to keep track of products being taken in or out of the facility and to update inventory databases of either raw materials or finished products. Technologies like bar code present limitations regarding the amount of time spent to check a unit load and its line of sight requirement. Using RFID, all elements of a unit load are tagged and a reader, located strategically, identifies all the elements that go through a passing area. However, the reading depends on the distances between the tags and the reader as well as the packaging materials used in the unit load that might affect the RF signal (Angulo et al., 2013).

D. PRODUCT DEVELOPMENT AND SYSTEMS ENGINEERING

The concept of product development is defined by Mital, Desai, Subramanina, & Mital (2014) as "the overall process of conceptualizing a product and designing, producing, and selling it". Essential for this process is an understanding of the user needs that customers want to see satisfied, and how much they are willing to pay for it (Mital et al., 2014).

Product development research was divided into three categories by Brown & Eisenhardt (1995), a rational plan perspective, a communication perspective, and a problem solving perspective. The rational plan emphasizes that successful product development is the result of careful planning and execution targeted to an attractive market, which is defined by identifying and understanding user needs. The communication perspective focuses on the role that communication plays in project teams to plan and execute product development activities. Lastly, the problem-solving perspective deals with management practices that aid the development process and studies the relationship between the autonomy of project teams, and leadership from top management.

In relation to the application of systems engineering (SE) techniques to new product development, Vanek, Jackson, Grzybowski, & Whiting (2017) studied the benefits that the application of SE techniques generate over the process of new product development in commercial enterprises. The authors found a positive association between high performing projects and utilization of SE techniques, and also found that projects with deficient performance were characterized by a lack of SE techniques implementation.

Systems Engineering is an interdisciplinary field that aims to tackle the growing complexity of sociotechnical systems characterized by the application of scientific principles to the design and development of systems, enabling their successful material realization (Ramos, Ferreira, & Barceló, 2012). This approach has been traditionally used in the development of aerospace and defense related systems, although its implementation in civil and commercial applications has gained ground in later years due to its demonstrated effectiveness to produce better performing outcomes (Vanek et al., 2017).

A systems engineering framework for system development is provided in the work of Sols (2019) that include a non-linear sequence of steps triggered by the identification of a need or the perception of a market opportunity and ends when the lifetime of the system expires. Figure 20 shows the framework provided by (Sols, 2019):

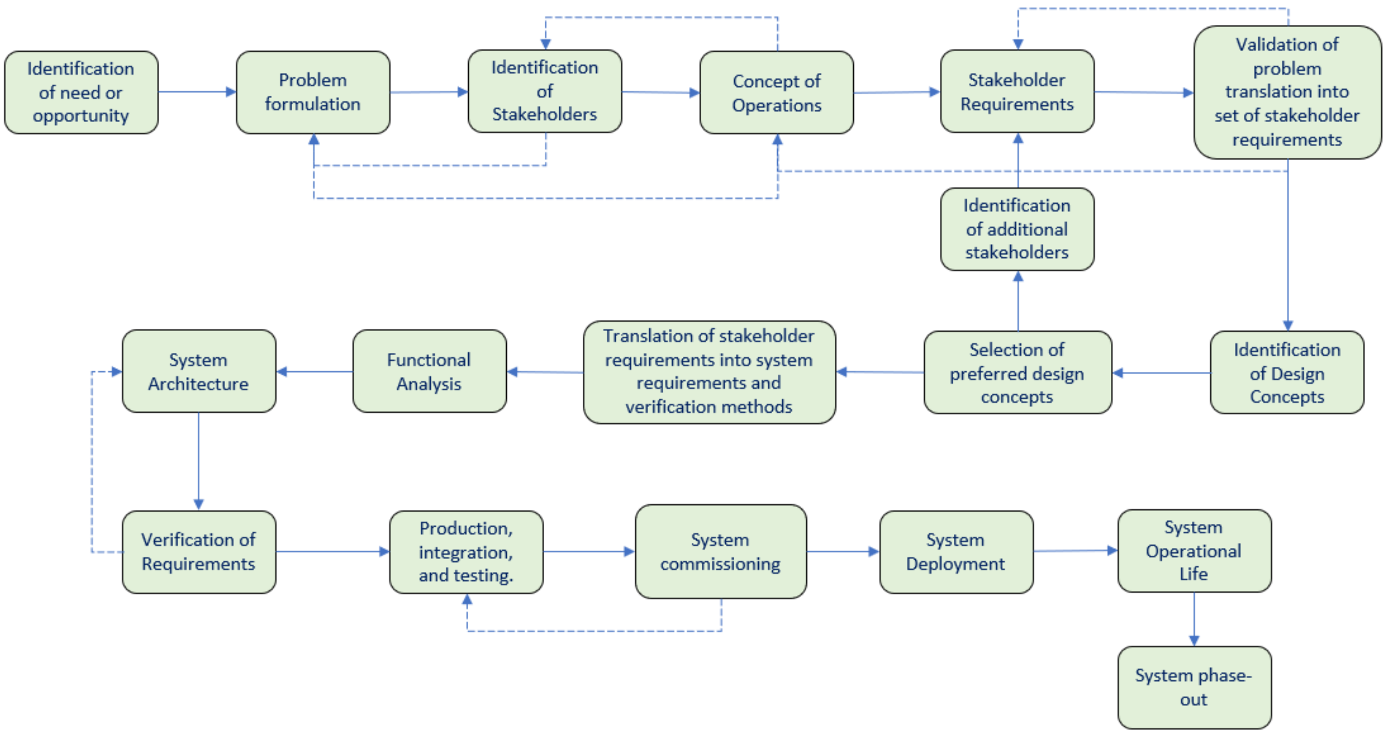

Figure 20. A Systems Engineering Framework for System Development (Sols, 2019).

The systems engineering approach includes management and technical processes. The management activities deal with planning, performance monitoring, risk management, project schedule, and budget, whereas technical processes deal with analysis, specification, design, and verification of the system and its components to ensure that the project objectives are met (Friedenthal, Moore, & Steiner, 2015).

III. GOALS AND OBJECTIVES

This project focuses on developing an operational concept of an IoT in order to satisfy distribution packaging and supply chain capability needs among industrial companies, and to discuss challenges and future research opportunities for the adoption of IoT technology.

Research Objectives:

1. To define capability needs for IoT that industrial companies have in relation to their distribution packaging supply chain.

2. To propose an IoT operational concept for the defined capability need related the distribution packaging supply chain.

3. To identify the main challenges for the adoption of the proposed operational concept in distribution packaging supply chain and future research opportunities.

IV. METHODOLOGY

There are three research questions formulated for this project:

- *Do companies have capability needs in their distribution packaging supply chain that makes necessary the adoption of a system?*
- *How can IoT technology be implemented to address the capability needs of companies in their distribution packaging supply chain?*
- *What are the challenges and limitations for companies to implement the proposed operational concept in their distribution packaging supply chain?*

The following methodology was carried out to answer the above formulated research questions:

Objective1: To define capability needs for IoT that industrial companies have in relation to their distribution packaging supply chain.

A. Capability Needs Identification

1. Case Study- Semi Structured Interviews

The second method utilized to identify capability needs was to conduct semi structured interviews with case study companies in fields related to product manufacturing, distribution packaging manufacturing, and product distribution.

The purpose of these interviews was to gather the perspective from different companies in regard to their distribution packaging capability needs. It was considered that following a case study approach using semi-structure interviews would allow to elicit this information given that case studies are useful in situations where inferences are descriptive rather than causal, when internal comparability is prioritized over representativeness, when the research strategy is exploratory, rather than confirmatory, and useful variance is available for only a single or reduce number of units (Gerring, 2004). A case study is understood as “an intensive study of a single unit for the purpose of understanding a larger class of similar units” (Gerring, 2004).

Other characteristics from case study approach that are aligned with the purpose of objective 1, in defining capability need are described by Gillham (2000):

- Non-experimental methods
- Subjectivity
- Participation
- The importance of context in shaping behavior
- Searching for evidence in context

The semi-structured interview strategy was adopted given that it allows to gather the perspective of interviewees on a given set of issues, because the interview is organized around a set of open-ended questions, and other questions might arise from the conversation between interviewer and interviewee (DiCicco-Bloom & Crabtree, 2006).

In total, eleven companies were contacted via phone calls to conduct semi structured interviews, a copy of which can be found in Appendix A. Relating to the work of Gerring (2004) on case study methodology, the unit of study for this case is composed of the eleven companies selected, the information collected is divided into several variables, which provide the observations for the case study. The people interviewed were predominantly company executives, packaging, and logistics engineers. These companies were selected based on their availability to participate in this study, and because their regular activities are related to the distribution of products by the utilization of industrial packaging. Five of the companies were contacted through the Center for Packaging and Unit Load Design (CPULD) at Virginia Tech, while the remaining 6 companies were contacted through the Reusable Packaging Association (RPA).

Objective 2: To propose an IoT operational concept for the defined capability need related the distribution packaging supply chain.

B. Operational Concept

1. Stakeholder identification

To identify stakeholders, an exploration of the system's relationships was carried out, given that a systems-thinking model-centric approach is most effective in correctly identifying all pertinent stakeholders through the description and exploration of relationships that occur as a product of the inherent behavior of the system, as suggested by Salado & Nilchiani (2013).

Based on the user needs identified, and using the questions presented in Figure 21 to explore the relationships that the system will exhibit in order to function, and to satisfy the user needs identified, a systemigram was used to guide the discovery of stakeholders.

Topic	Sample questions
Why	Why having this system? Why does the stakeholder do/want/react/interact/etc. that?
How	How does the system work/operate/behave/etc.? How is the system designed/built/operated/challenged/disposed/etc.? How does the stakeholder play/act/operate/think/decide/etc.?
Where	Where does the system work/operate/behave/etc.? Where is the system designed/built/operated/challenged/disposed/etc.? Where does the stakeholder play/act/operate/think/decide/etc.?
What	What does the system do? What is the system expected to do/make of/etc.? What does the stakeholder do/want/behave/decide/etc.?

Figure 21. Guiding Questions to Explore Relations of the System and Discover Stakeholders (Salado & Nilchiani, 2013).

2. System Model

The operational concept proposed in this project was developed based on a systems engineering framework that leverages on the application of model-based systems engineering (MBSE). MBSE can be understood as the application of models to support system solutions in response to stakeholder needs (Friedenthal et al., 2015). A model is a graphical representation of reality that employs abstraction to simplify and understand it from a certain point of view (Ramos et al., 2012).

As part of the systems engineering framework, a tool called the "concept of operations" (conops), was used to provide a visual representation of the system, the capabilities that are currently in place with a current system, and what will be achieved by the proposed new system concept. The model for this project consists of a set of diagrams that represent the interactions or behaviors of the system from different functionalities' perspective. These diagrams were created using Cameo Systems Modeler, a system modelling software that utilizes the SysML modeling language, which is the basis for structured system modelling. The diagrams employed were:

- Use case diagrams
- Sequence diagrams
- State machine diagrams

The application of a model-based approach to systems design has been found to have several advantages for the design effort, which according to Friedenthal et al. (2015), include the following:

- Enhanced communication among members of the development team and stakeholders.
- Higher quality requirements.
- More effective comparison of different design alternatives.
- Lower error rate during integration and testing.

It is important to state that the application of MBSE encompasses the total process of system design through the successful materialization of the physical system, its verification, and its validation. The use of MBSE in this project is limited to depictions of the system's concept, and the logical design, which are technology independent. An additional intention is to show how this approach can be used to address the development of systems that bring together the industrial packaging industry and the technology industry in order to tackle operational problems and conceive innovative solutions.

3. System Architecture

The architecture of a system is understood as a set of principles, guidelines, relationships, concepts and properties that govern the system design and evolution (Luzeaux, 2014; Schaible, Scolese, Ryschkewitsch, Verma, & Larson, 2014). The ISO/IEC/IEEE 42010 international standard defines a system's architecture as "fundamental concepts or properties of a system in its environment embodies in its elements, relationships, and in the principles of its design and evolution" (IEEE, 2011).

For this project, the architecture of the system was defined from two points of view: functional, and physical. The functional architecture describes the capabilities, services and functions provided by the system to satisfy an operational concept. The physical architecture specifies the solution's components that will perform the functions to meet the operational requirements

To establish the two architectures, the following steps were followed:

- System functions identification.
- Identifying functions inputs and outputs.
- Establishment of functions structure.
- Determination of the physical elements.
- Functions allocation to physical components.

Techniques used to represent the functional architecture of the system will include functional block diagrams (FBD diagrams), as suggested by Schaible et al. (2014). In addition, system requirements, stakeholder priorities, and a concept of operations will be used as an input to identify the system's functions.

Objective 3: To identify the main challenges for the adoption of the proposed operational concept and future research opportunities.

C. Challenges for the Implementation of the Proposed Operational Concept.

Based on the results obtained through the activities carried out for objective 2, a discussion of challenges, possible solutions, and areas where further research is required for the implementation of the proposed operational concept in palletized supply chains is presented. This analysis stems from reflecting on the capability needs found to accomplish objective 1, on the practical implementation of the operational concept proposed to accomplish objective 2 and supported through the use of references from the literature.

V. RESULTS AND DISCUSSION

A. USER NEEDS IDENTIFICATION

Table 3 shows a summary of the information collected during semi-structured interviews conducted with 11 companies. The companies interviewed were selected based on their availability to participate in the study and because their activities require or are related to the distribution of products by utilizing industrial packaging. It is important to state that these findings cannot be taken as a representation of the overall needs that exist in the industry in regard to distribution packaging processes. However, it serves to provide an example of the needs from the perspective of different types of companies.

One of the most crucial insights obtained from these interviews is that the type of information needed is dependent on the type of product being distributed and the type of supply chain through which it flows. For example, companies that manufacture packaging for the pharmaceutical and food industries expressed that they place a higher importance of safety and cleanliness for their applications.

In general, most companies manifest an interest in location tracking. Mainly, this is with the purpose of providing visibility in their distribution processes, controlling the routes on which their products travel, managing lead times, and discovering unknown points of departure or delay. Also, in the case of reusable packaging, there is an interest in having the ability to track and locate each packaging unit. Reusable packaging units are company assets that must be prevented from being lost.

Most of the companies interviewed utilize international standards to design their packaging or they subcontract out the designing of their packaging. Two of the interviewees stated that the standards are too aggressive or not aligned with their particular supply chain conditions. One of the companies interviewed expressed concern about implementing technology in their packaging solutions regarding what would happen to the physical technology infrastructure once the packaging unit reached its lifetime. This is an important consideration to account for when planning for IoT technology infrastructure to be installed in reusable packaging.

Table 3. Summary of Information Collected During Interviews with Companies.

Type of Company	Role of people Interviewed	Customers by industry	Main Distribution Hazards	Information aiding current packaging design	Distribution parameters of interest
Reversed logistics solutions provider	Director of Business Solutions	Electronics Industrial equipment	Material Handling Temperature Relative Humidity Vibration during transportation Lost products	The company does not design the packaging.	Temperature Humidity Location Vibration Shock
Reusable plastic container manufacturer	Vice President	Produce Meat	Temperature		Location Temperature Vibration Shock
Reusable plastic container manufacturer	Director of logistics and asset management	Produce Meat	Temperature Unknown control of RPC	Material handling system where RPC will be used	Location Temperature Vibration Shock
Cabinet Manufacturer	Product Development Engineer	General Public	Material handling Vibration during transportation	ISTA standards, tailored with internal company information about their supply chain.	Location Shock Vibration
Electronics Manufacturer	Packaging Engineer	General enterprises	Material Handling Changes in relative humidity	ISTA standards Internal standards based on ISTA	Relative Humidity Shock Vibration
Biotechnology	Packaging Engineer	Pharmaceutical Biotechnology Research Government Academic	Shock Temperature	ISTA standards	Temperature Shock Vibration
Plastic Pallet Pooler	Chief Operating Officer	Printing	Material Handling	Standards	None
Plastic Pallet Manufacturer	Vice President	Food Pharmaceutical	Temperature	Standards	Shock Location Temperature Vibration
Medical equipment manufacturer	Packaging Engineer	Healthcare	Handling Shock	ISTA and ASTM standards	Shock Vibration Temperature Location
Automotive	Packaging Engineer	General Public	Material Handling	Internal information about their supply chain	Shock Relative Humidity Vibration Location
Food/Consumer goods	Logistics Manager	Retail Stores	Material Handling Temperature	ISTA standards Internal company information	Temperature Location

Given the information gathered from the case study companies interviewed, a list of user needs is derived, which are shown in Table 4. The user needs are understood as things that the user has an interest in doing in order to achieve or preserve something of value. In the context of distribution packaging, this is understood as the necessity for companies to be able to preserve the value of their products during transportation and the ability to satisfy their customers.

Table 4. User Needs Statements.

User needs statements
UN1. The user needs to know the location of products as they are being distributed along the supply chain.
UN2. The user needs to avoid the damage of products and packaging that results from changes in temperature during distribution.
UN3. The user needs to avoid the damage of products and packaging that results from changes in relative humidity during distribution.
UN4. The user needs to avoid damage of products and packaging that result from shock events during distribution.
UN5. The user needs to avoid damage of products and packaging that result from random vibration during transportation.
UN6. The user needs to access captured data remotely.
UN7. The user needs to optimize package design to provide product protection at minimum cost.
UN8. The user needs to be notified when temperature, humidity, or shock registered by a pallet falls out of a predefined threshold level.

The following section describes the distribution parameters that were found to be important for companies, and their role in distribution packaging:

1. Temperature and Relative Humidity

Monitoring the temperatures to which products are exposed during transportation is critical in many industrial scenarios. Existing examples of these applications are found in the produce industry, where damages during transportation can be prevented by monitoring the temperature of sensitive products. Changes in temperature can lead to product spoilage, resulting in product losses and increasing the risk of negative impacts to consumer health. Vaccines and many other pharmaceuticals are also examples of products that are sensitive to temperature. They must be handled following restrictive procedures that demand the products be carried “in cold” throughout the supply chain (Tsang et al., 2018).

Temperature and humidity have the potential to harm both products and packaging materials. High temperatures have been found for instance to have a relaxation effect on stretch film, reducing its containment force and potentially compromising the stability of unit loads. In addition, increase in humidity can lead to the softening of carton-type packaging and sometimes even to condensation forming inside the packaging (Fragassa, Macaluso, Vaccari, & Lucisano, 2017).

2. Shock

In the packaging and product distribution context, shock is understood as a change in the equilibrium of the package-product system caused by a rapid acceleration, or deceleration, in a short period of time; usually, this is inflicted by material handling or transportation equipment (Blumer & Guadagnini, 2011).

When a unit load experiences a shock event during distribution, an impact wave is transmitted across the entire unit load. The ratio between the shock output from an object to the input is known as transmissibility (Blumer & Guadagnini, 2011). In the case of a unit load, when this ratio is less than one, it means that part of the energy of the shock was absorbed by the unit load in what is known as the damping effect. If the ratio is more than one, it means that the unit load actually increased the intensity of the shock wave, which happens when there is resonance with the unit load.

A mechanical shock occurs when an object’s position, velocity or acceleration suddenly changes. The damages of packages are related to three shock related variables: peak acceleration, duration, and velocity change. By knowing any two of these variables, it is possible to compute the third one (Brandenburg & Lee, 2001).

Brandenburg & Lee (2001) argue that the shock environment characterization requires knowledge about the typical drop heights for the product in question. This study contends that part of that characterization can also be achieved by measuring shock intensity during transportation and handling at the unit load level.

3. Vibration

Vibration is generated during the operation of vehicles as a result of the dynamic interaction between the vehicle and the physical elements with which it interfaces in order to move (road, railroad, water, air, space). Some examples of these interactions are between the road and the truck, the railroad and the train, or the air and the airplane. The behavior of vibration is rough, rambling, and random. Transportation and handling activities during global distribution are known to generate vibration that has the potential to damage products. Furthermore, understanding the effects of vehicle vibration on products is important in aiding packaging design (Rouillard, 2008).

There are several variables that influence the behavior of vehicle vibration experienced by the products:

- The type of vehicle.
- The physical elements' conditions: condition of the railroad tracks, road/asphalt conditions, turbulences in air, movement in the sea.
- The type of load in the container.
- Weight on the pallet.
- Location of the unit load in the container.
- Location of the product in the unit load.
- Tire pressure (in the case of wheeled vehicles).
- Suspension type and condition (in the case of trucks).

Traditionally, in order to design protective packaging solutions to withstand the hazards experienced in a distribution supply chain, performance testing of packaging systems has been carried out using laboratory testing to recreate the conditions that the packages are expected to experience during distribution in real life (Rouillard, 2008). However, this approach entails significant limitations. First of all, it assumes that given a vehicle type, all vehicles belonging to that category will behave the same, which is not accurate in practice. Second, it does not account for the constant change in road and rail conditions, during ground transportation.

As a result of these testing limitations, companies usually adopt a conservative approach and design their packages based on a worst-case scenario in order to increase the probability of products surviving and remaining undamaged. This situation causes many products to be overpackaged, which translates into higher packaging costs and more wasted materials (Rouillard, 2008). This study contends that the ability to know the vibration levels, as well as other important parameters taking place during distribution, in a continuous fashion will allow the optimization of packaging designs adjusted to a company's supply chain's specific conditions and performance requirements. In other words, knowing this information will allow for full customization of packaging designs based on factors like type of transportation, types of vehicle, and road conditions. And changes in any of these factors would be captured in a timely manner, and corrective measures would be more expedited.

Vertical vibration is widely accepted to be one of the conditions most directly related to product damage during transportation (Rouillard, 2008). In order to design packages that prevent these damages, the distribution environment in which a product will be shipped must be carefully identified and characterized (Brandenburg & Lee, 2001). A useful way to characterize the vibration that occurs during distribution is in the form of a power spectral density plot (PSD), which shows the average intensity of the vibration against the frequency of the vibration. An example of a PSD plot is shown in Figure 22:

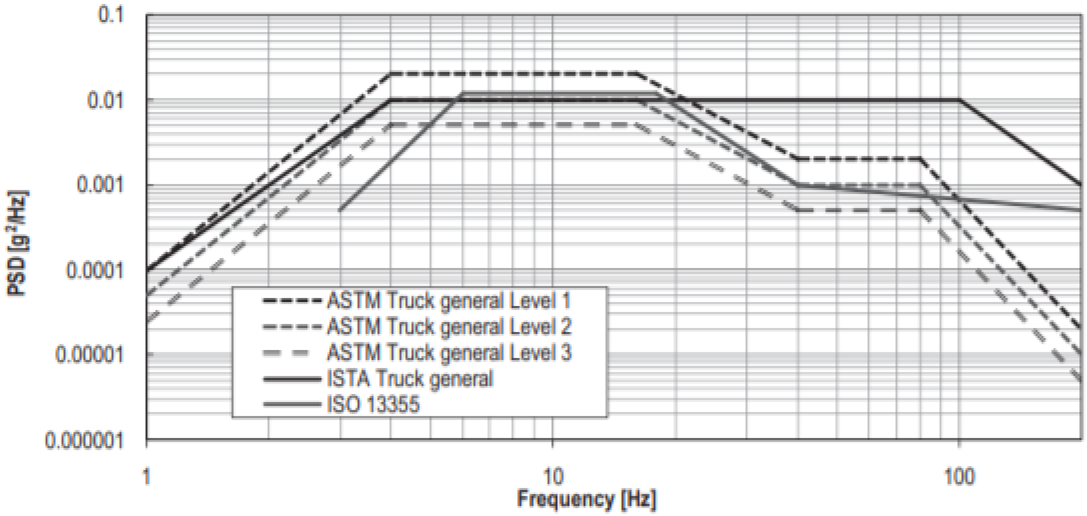

Figure 22. Example of PSD Plot Showing the Average Intensity of Vibration Against the Frequency of Vibration in a Logarithmic Scale (Rouillard, 2008).

Designing protective packaging that protects products from vibration damage requires knowledge about the range of frequencies present in the distribution environment and the intensity associated with each frequency. In addition, it is also necessary to know the level of vibration that results in damage for the product. Usually, products are damaged when vibration frequency reaching the product matches the natural frequency of the product or its components. This results in a resonance that amplifies acceleration and displacement which causes product failure. By knowing the profile of the vibrations that will be experienced throughout the distribution process, packaging can be designed to attenuate the vibrations that match product's natural frequencies. This ensures that any vibrations that do reach the product do not cause resonance and failure (Goodwin & Young, 2011).

The theory behind interactions of shock and vibration with products has been well developed, and it is found in the works of authors like Brandenburg & Lee (2001), and Goodwin & Young (2011). Therefore, the problem of inefficient packaging design is not from a lack of understanding the effect of environmental variables on the products, but rather from an inability to know these variables in a reliable and precise way.

4. Location

One of the most desired features in a supply chain is visibility and coordination (Dubey et al., 2018; Li, Zhao, & Huo, 2018). However, as the number of actors participating, and the complexity of the supply chain increases, visibility and coordination becomes more challenging, making it difficult to achieve an end-to-end view (Argon Consuting & Sigfox, 2018).

The inability to easily visualize every step of the supply chain causes accuracy reduction in planning, less options for managers, and increased lead times. As the implementation of the internet of things (IoT) approach to supply chain and logistics aims to provide end-to-end visibility, this technology sets the foundation for reducing lead times along the supply chain, by increasing efficiency and productivity in all production phases that are dependent on the chain's performance (Argon Consuting & Sigfox, 2018). A good example is the retail industry, where the manufacturer's scheduling processes can be synchronized with the real-time demand of stores, assuming the supplier can integrate stock and sales data from the retailer (Bandyopadhyay & Sen, 2011). This requires a close collaboration between multiple entities in order to introduce transparency in all of the steps that a product goes through along the supply chain (Tjahjono, Esplugues, Ares, & Pelaez, 2017).

IoT technology will allow for this transparent virtualization of the entire supply chain, enabling stakeholders to track and trace the flow of goods, and obtain valuable information like the quality status of products, and it will allow for better planning and synchronization (Ben-Daya, Hassini, & Bahroun, 2017).

However, from a packaging standpoint, the main interest lies in knowing the location of specific points of the supply chain where high levels of vibration or shock take place, or where temperature and relative humidity can compromise the products. This information allows for an accurate map of distribution hazards along a supply chain to be achieved, which increases the certainty about physical conditions of the supply chain, and will help in quickly identifying and making corrections for any changes that occur.

B. OPERATIONAL CONCEPT

1. Stakeholder Identification

From a system development standpoint, a stakeholder is a person or institution that is interested in, can be affected by, or can have an influence on the utilization or performance of the system (Sols, 2019). In order to identify the stakeholders that interact with a potential IoT system, it is necessary to have a notion of the purpose of the system, its operational context, and the initial customer expectations for the system. In this study, the customer is understood to be the industrial company that manufactures a certain type of product, which will be distributed down the supply chain using packaging and pallets.

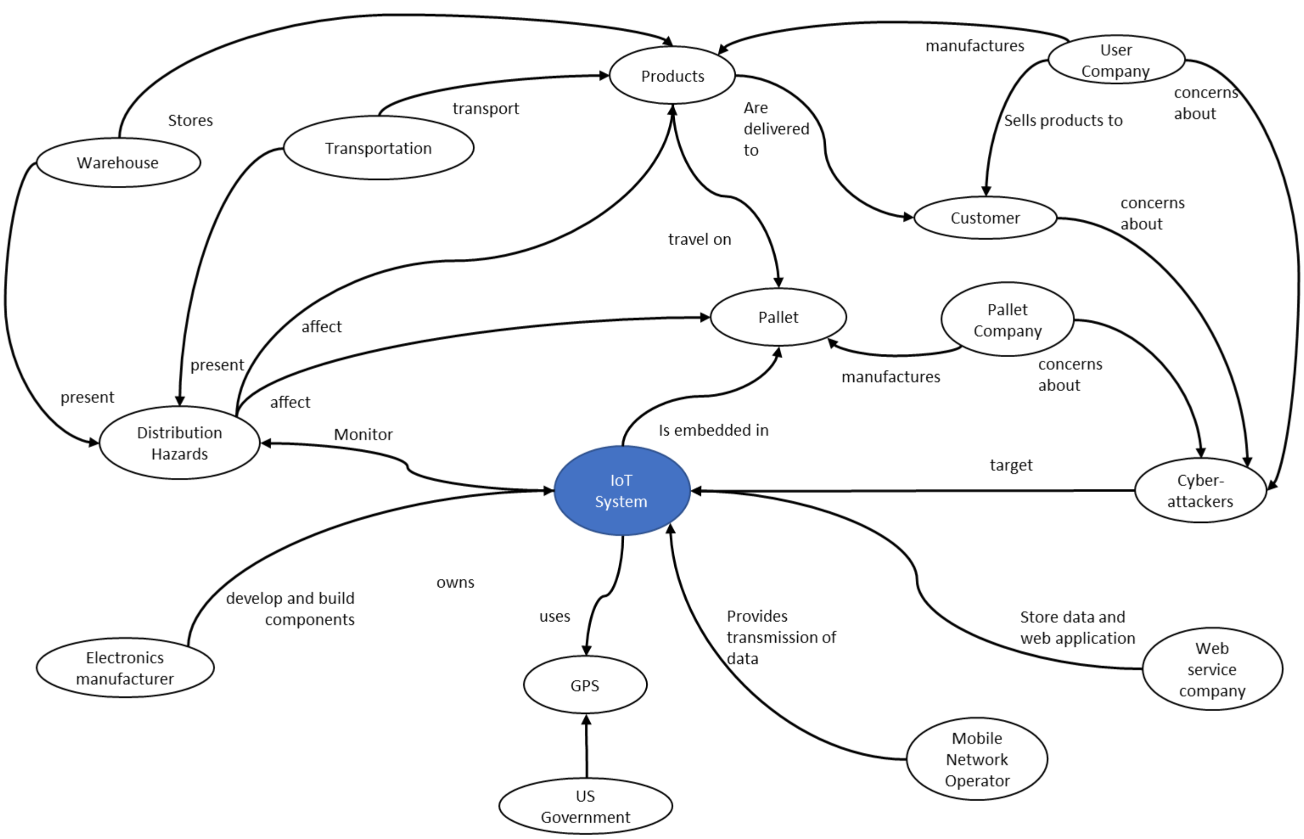

Figure 23. Systemigram of an IoT System for Distribution Packaging.

The systemigram shown in Figure 23 exhibits the relationships of the IoT system based on the initial customer expectations. From these relationships and interactions, the following set of stakeholders can be identified:

STK1. User companies: The users of the system are product manufacturers that need to track the location and conditions of their products to assure their integrity during distribution along the supply chain.

STK2. Cyber-attackers: The nature of remotely operated systems imply the wireless transmission of data; this creates the risk of bad actors wanting to steal, manipulate, and sabotage the system and its data. For this reason, they should be considered stakeholders, and must be accounted for when designing the IoT system and its capabilities.

STK3. Mobile network operator: The transmission of data from products to the cloud often takes place outside of facilities and away from the company's local area networks; hence it might require the use of cellular networks provided by mobile network operators.

STK4. Pallet manufacturers: Most products are transported and stored in warehouses supported by pallets. As this element is ubiquitous in the distribution of products, it is a hub in which to physically allocate infrastructure in order to capture distribution hazards data. This makes the pallet manufacturers stakeholders in the system.

STK5. Electronics manufacturers: Electronics companies manufacture sensors, microcontrollers, and transmission mechanisms necessary to perform the functions needed for an IoT system. The technologies that these companies develop provide the system with the ability to deliver the needed information to the customers.

STK6. Transportation companies: The transportation of products can occur in different ways: land transportation using trucks or railroads, air transportation by planes, and sea transportation on vessels. These transportation activities might be carried out by third parties or by the company itself. IoT systems may require the deployment of technology on trucks or other means of transportation; therefore, it is necessary to consider them stakeholders in the system.

STK7. Warehousing companies: warehousing can also be outsourced to external parties. If so, the IoT system needs to be deployed within these facilities; otherwise, it could be integrated within the company's own warehousing systems. Either way, warehouses must be considered stakeholders.

STK8. Customer: Customer refers to the final point of delivery for products. Tracking the location and condition of products as they move downstream in the supply chain requires integration or the deployment of infrastructure at the point of delivery.

STK9. Government: One of the needs previously noted for IoT system is the ability to track the location of products remotely. Outside of facilities with local area networks, the Global Positioning System, owned by the United States Government and administered by the United States Airforce, must be employed to achieve that purpose. In addition, the government regulates electronics companies and, mobile networks operators. It has a special interest in cybersecurity and has recently adopted measures to constraint the adoption of certain types of wireless infrastructure technology (Bloomberg News, 2019).

2. Concept of Operations

The purpose of the concept of operations, or conops, is to show an "As-Is" –"To-Be" situation that illustrates the way in which something is used at the present time, as opposed to how it will be used in the future by utilizing the proposed system or approach. In this context, the "As-Is" scenario explains the capabilities that a company has with the current packaging solutions available, whereas the "To-Be" scenario shows the capabilities that are to be achieved by integrating IoT technologies into their packaging systems.

2.1 The Current State

Figure 26 describes the "As-Is" scenario. This example shows reusable pool pallets which the manufacturer uses to transport its products down the supply chain, either directly to a customer, to a distribution center, or warehouse in which the unitized load is stored and then later redirected to its final customer. Once the unit load arrives at its final destination, assuming there were no picking processes along the way, the product on the pallet is unloaded, and the pallet is put aside to be picked up by the pallet pooler company. They take care of repairing the pallet, recycling it, disposing of it, or re-allocating it. In this scenario, the role of the pallet, as it pertains to the unitized load, is limited to the protection of the product and enabling its movement during distribution.

The movement of finished products, from the manufacturer to the final point of consumption, implies the physical movement of a product from the manufacturer through a series of nodes down the supply chain until it reaches the customer. This movement varies depending on many factors, such as type of product and destination point. An example of the movement of products from point of manufacturing to point of consumption is presented in Figure 24.

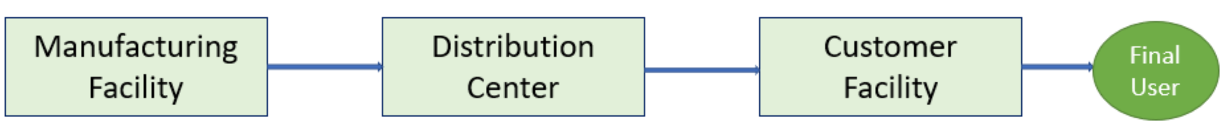

Figure 24. Example of Movement of Products from Point of Manufacturing to Point of Consumption.

The example presented in Figure 24 shows a product that is taken from the manufacturer to a distribution center, then transported to a retailer where it is finally purchased by the consumer. All of these movements imply that the product interacting with multiple external conditions known as distribution hazards: shock, vibration, compression, and atmospheric.

Shock refers to the forces that products experience while they are being moved with material handling equipment, like pallet jacks, forklifts, and conveyor. They also experience shocks during transportation when they are subject to the forces produced by jumps or sudden breaks in motion. Vibration is transmitted to the products during movement by the equipment being used to move them: trucks, parcel delivery vehicles, airplanes, rail carts, and vessels. Compression refers to the forces the products are subjected to as the result of being stored and transported with other products in the form of consolidated unit loads or double stacks. Double stacks are one unit load being stored and transported on top of another unit load.

Lastly, atmospheric conditions refer to conditions relating to the environment in which the product exists, like temperature, relative humidity, and pressure. In the example in Figure 24, a product that is transported from one country to another or even to different places within the same country, can experience different climates that causes changes in temperature, pressure, and relative humidity, all of which interact with the product. The role of distribution packaging during the distribution of products along the supply chain is to minimize the negative effects that these hazards pose to the products being transported and help guarantee that the product reaches the customer in an acceptable condition in order to achieve consumer satisfaction.

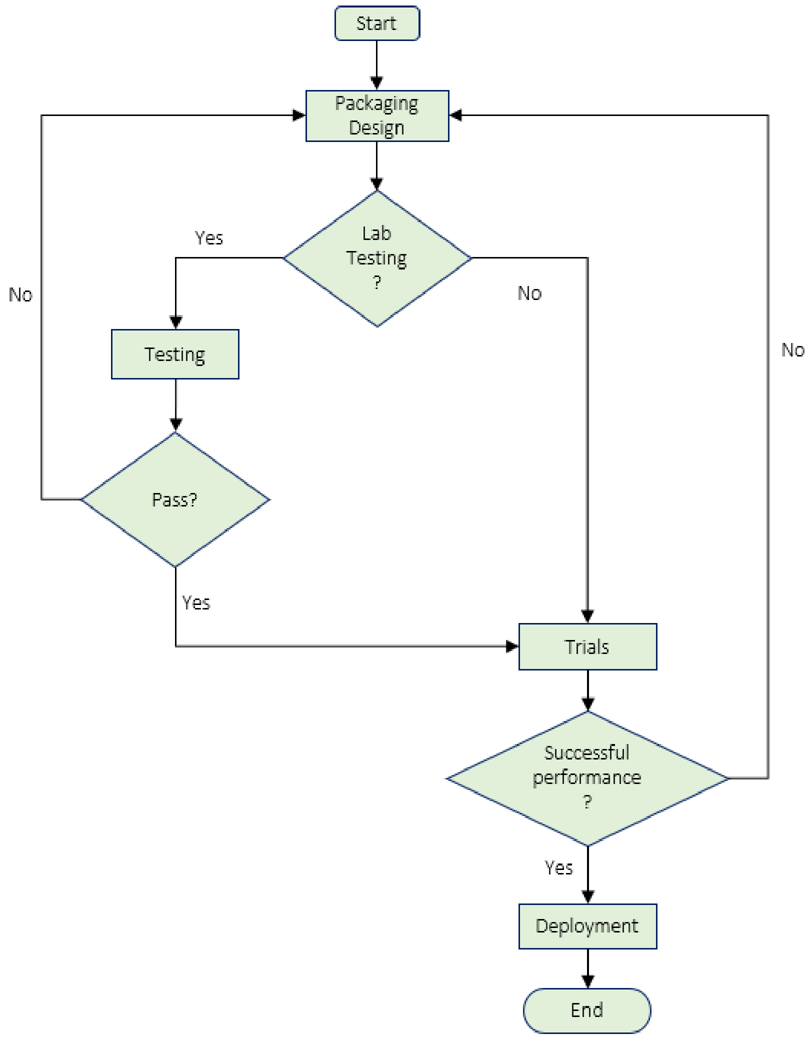

Figure 25. Decision Making Process in Packaging Design.

The flow diagram shown in Figure 25 describes the development process for new distribution packaging design. In the diagram, rectangles represent processes, and diamonds represent decisions. When designing a distribution packaging solution for a specific product to be deployed into the distribution supply chain, a company needs to have a sense of the physical conditions that the packages and products are going to experience along the supply chain. Once a design solution is chosen, the company needs to decide whether or not to proceed with laboratory testing. Testing is usually carried out following standardized sequences that are meant to resemble the exact conditions that the packages and products will face along the distribution supply chain. A prerequisite for successful simulation is prior knowledge about supply chain. The specific conditions of the supply chain will vary from case to case as different companies use different means of transportation, different material handling systems, and distribute across varied geographical areas.

If the results of the laboratory testing indicate that the packaging will successfully protect the product given their distribution supply chain's specific conditions, then the packaging is deployed; otherwise, the packaging is redesigned and might or might not be tested again. Once a packaging solution has been selected and deployed, the real distribution conditions, as well as the solution selected will influence the performance of the packaging. If the performance is satisfactory, then the process ends; otherwise, the packaging solution is redesigned yet again.

Because of the high uncertainty associated with which distribution hazards are present during handling and transportation, and their intensity, companies are usually left with a choice between two strategies. Either they must choose to accept the losses resulting from inadequate packaging solutions, or they must increase the level of protection by overpackaging, which increases packaging costs and decreases operational efficiency (Fragassa et al., 2017). This study contends that by having greater certainty about the conditions present in the distribution supply chain, it is possible to design more efficient, effective, and appropriate packaging solutions for any given product.

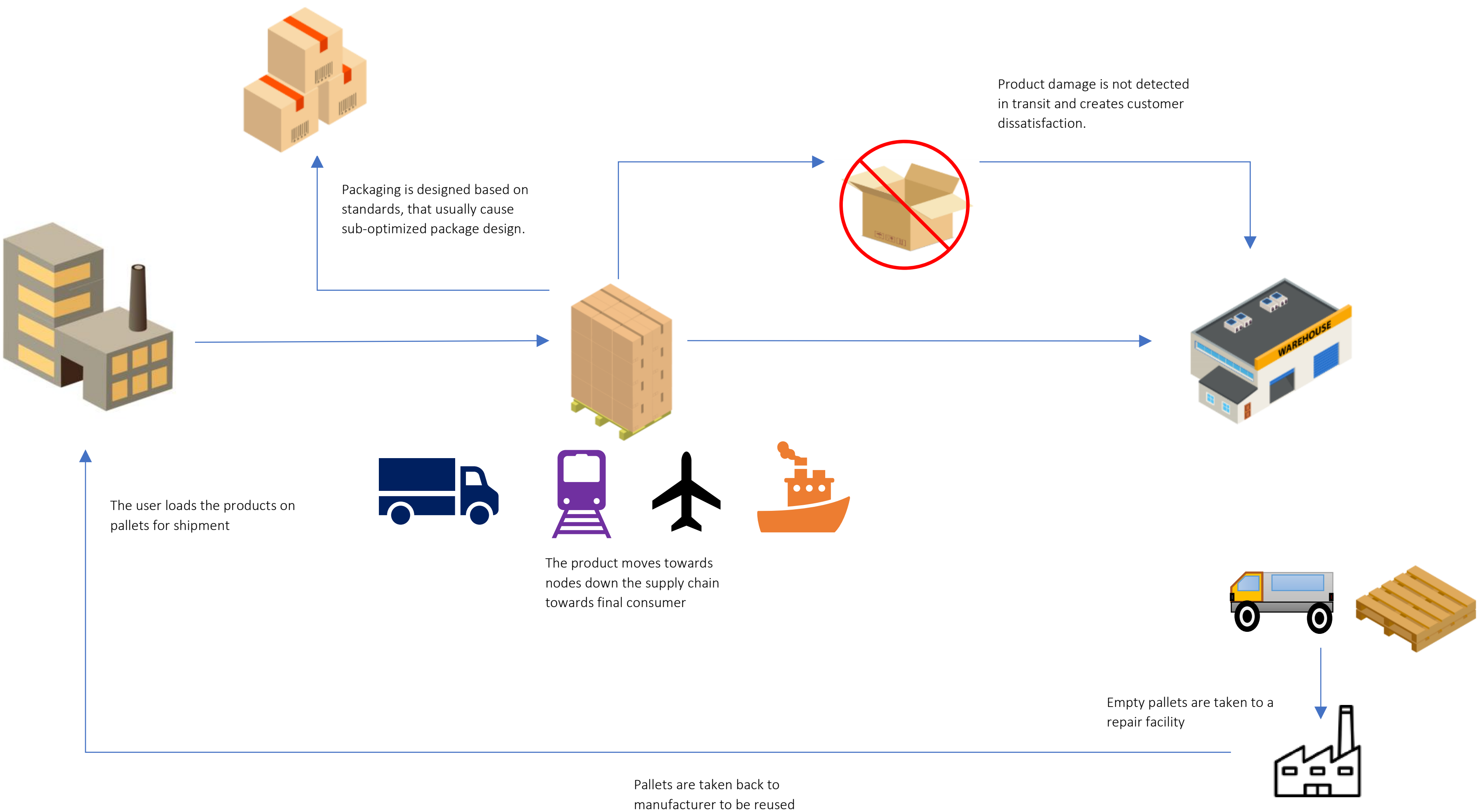

Figure 26. As-Is Scenario Concept of Operations.

2.2The Future State

The “To-Be” scenario is presented in Figure 27. In this scenario, besides the functions mentioned before, the pallet also acts as an agent to collect information about the environment through which it travels. Specifically, the pallet collects information about the environmental parameters that were defined by the user needs identified, and described in section A: temperature, relative humidity, vibration, shock, and location. At the end of the trip, the pallet stops collecting data, and is picked up by a pallet pooler to be re-allocated, repaired, recycled, or disposed of.

In this future state, the product location is captured as it moves along the supply chain towards the customer. Based on the user’s knowledge about the sensitivity of its products, when one of the parameters exceeds a predefined threshold, the user receives an alarm notification indicating the anomaly. This can trigger further control processes, like stopping the cargo in transit for inspection, assuring that any damaged product does not reach the customer, if it is already damaged, or to take timely corrective action, so that the product is prevented from getting damaged.

Furthermore, the distribution environment characterization provided by the system enables the optimization of packaging design. This is because the collected data allows to recreate distribution conditions more accurately than what current standards allow, which has a positive impact to design packaging that adequately protects products, with the least use of material, hence reducing cost, and increasing efficiency.

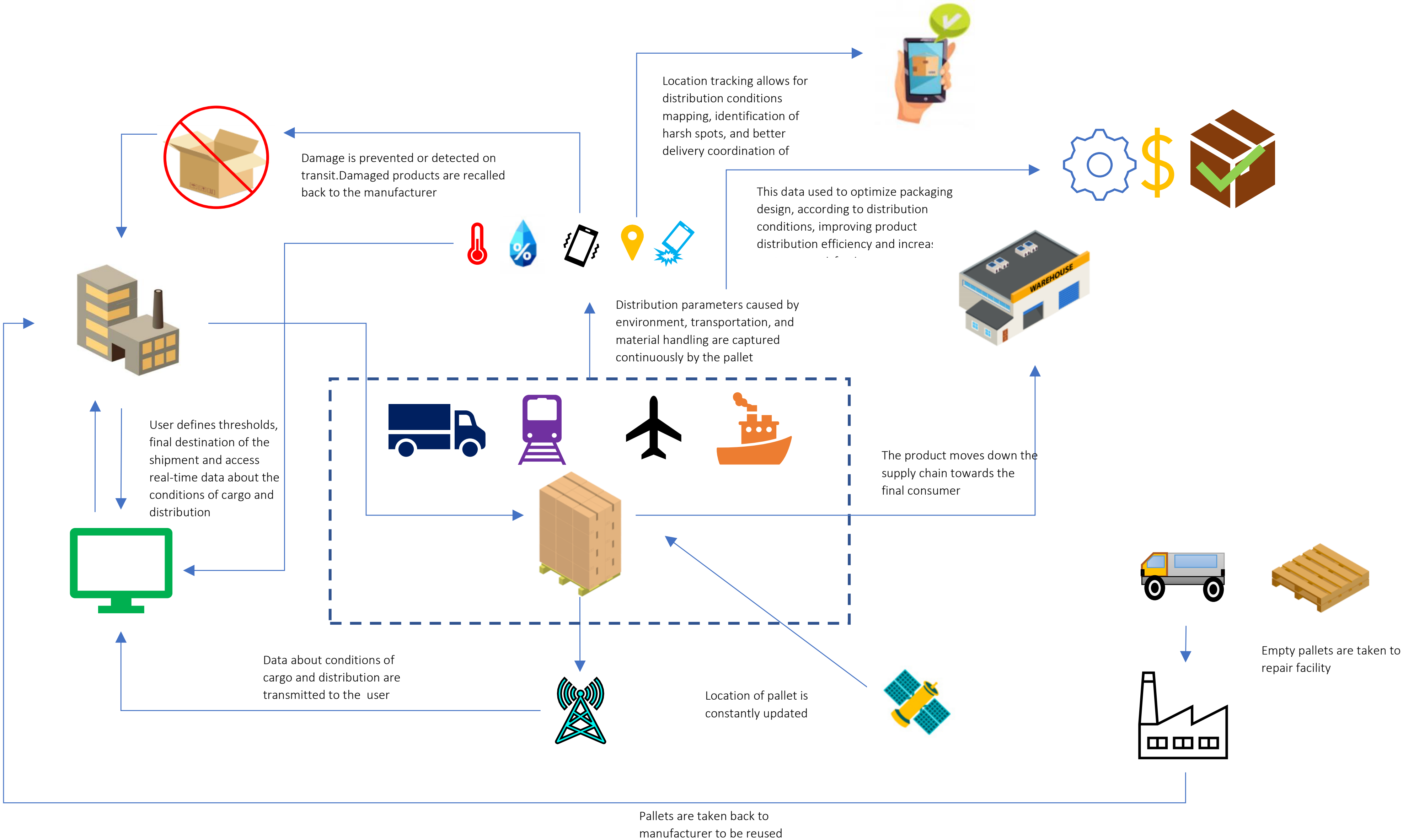

Figure 27. To-Be Scenario Concept of Operation.

3. System Model

3.1 System Context

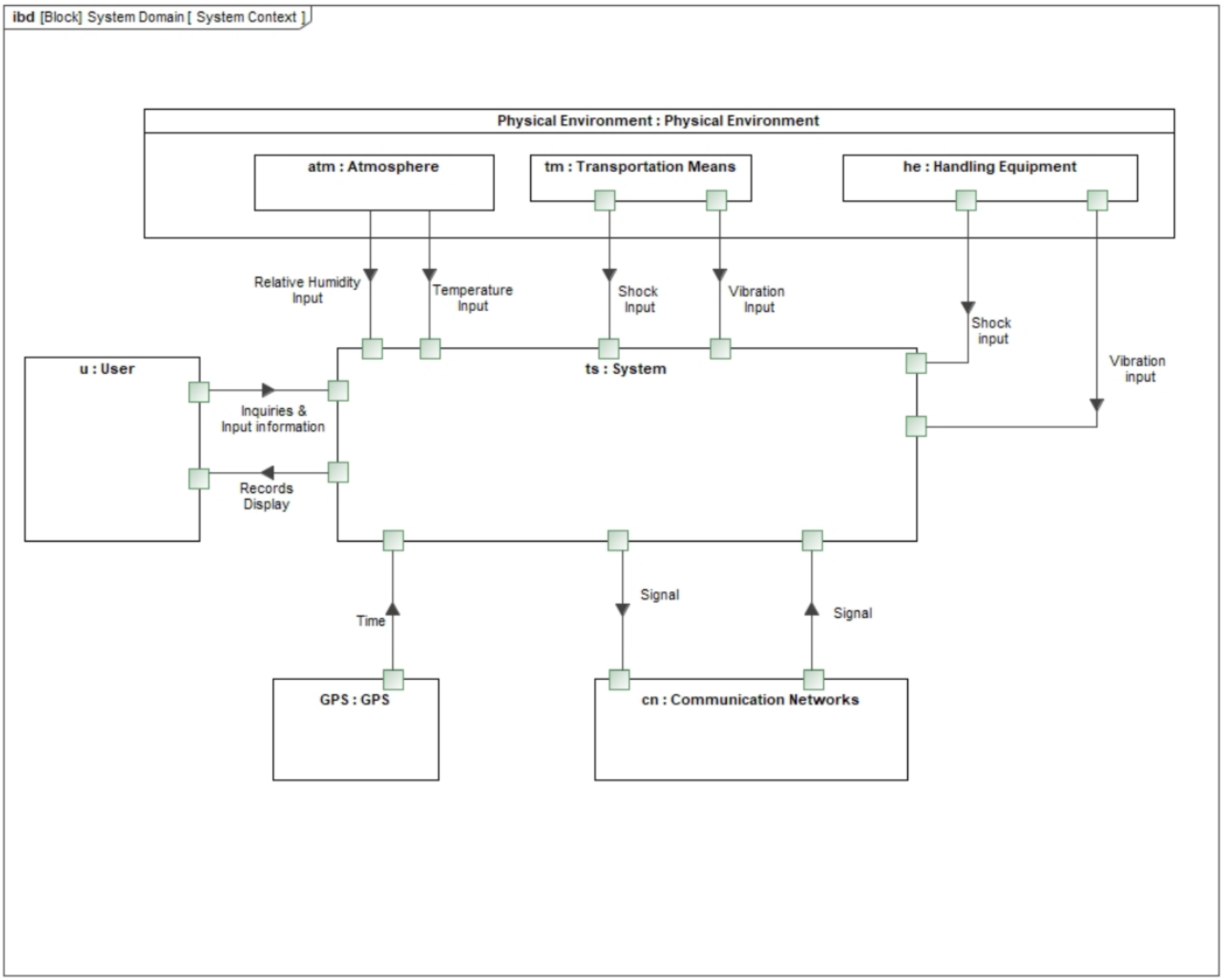

Figure 28. System Context.

Figure 28 shows the system context. Here the system boundary is defined by establishing the interactions that the system exhibits. From the concept of operations explained in section C.1, it is known that the capabilities required from the system are to collect data about the environmental parameters experienced during transit, between the different stages of the supply chain.

In order to achieve its purpose, the IoT system must interact with the physical environment to collect the inputs for the collection of distribution parameters. This physical environment has been broken down into three elements. First, the atmosphere, from which the IoT system senses temperature and relative humidity. Then the transportation modes, which transmits shock impulses and random vibration to the IoT system, and third, the material handling systems, which also provide shock and vibration data to the IoT system.

There are two basic types of user interactions defined by the diagram for this relationship. The first is called “inquiries & input information”. This is the interaction that takes place when the user provides instruction to the system about how to function under specific scenarios, as well as when the user makes inquiries about the data collected by the system. The second interaction is called “records display”. This type of user interaction occurs when the system displays all recorded information relating to the shipment.

3.2 Use Case Diagram

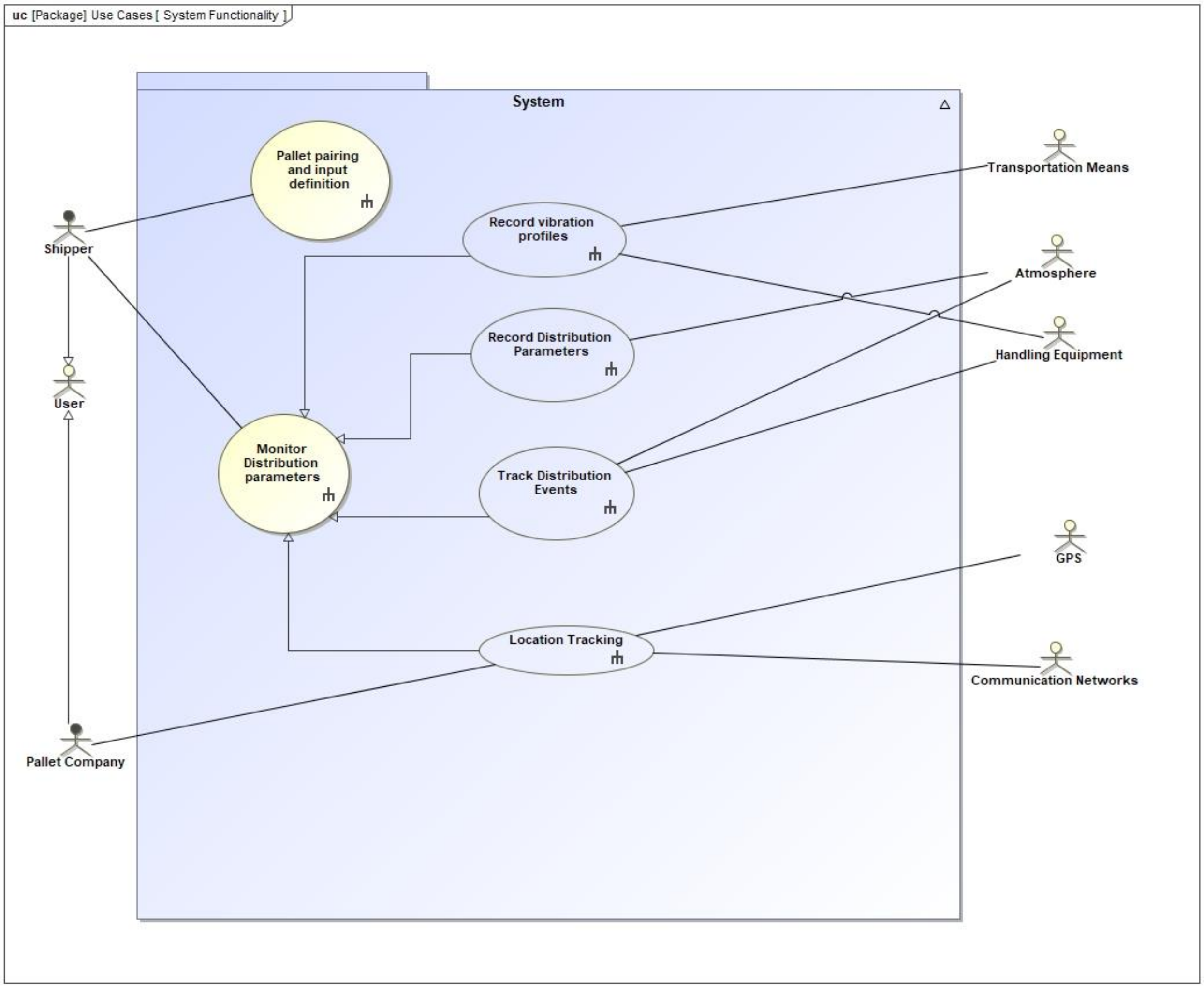

Figure 29. System Use Case Diagram.

A use case diagram shows several use cases intended for the system from the user point of view. The use cases are useful in communicating the functionalities of the system in a simple way. Figure 29 shows the different functionalities and the actors that interact with the system when one of the functionalities is activated. Actors are either users of the system, or external systems that interact with it.

The proposed system has two basic functionalities. The first is called “Pallet pairing and input definition”. As Figure 29 shows, it is the shipper who interacts with the system to define the thresholds and final destination settings that are necessary to support the other functions.

It must be noticed that users are divided into the shipping company and the pallet company. This is because this model is oriented for companies that use a pallet pool management system; therefore, their pallets are owned by the pallet pooler. Thus, some of the functions can only be triggered by the shipper, and others by either “shipper” or “pallet company”. Location tracking, which is of special interest to a pallet pooler in order to track down the location of their pallets and make sure they are recovered, can be triggered by either user.

The second functionality is called “Monitor Distribution Parameters”. Most other functionalities are generalizations of “Monitor Distribution Parameters”, or sub-functions that are derived from it. Figure 29 also shows the different actors that interact with the system when each specific function runs. For example, in order to execute the function “Record vibration profiles”, the must system interact with the transportation means, but such interaction is not required for the function “Location Tracking.” The specifics of each function will be explained in detail in the diagrams.

4. System interactions

4.1 Pallet pairing and input definition

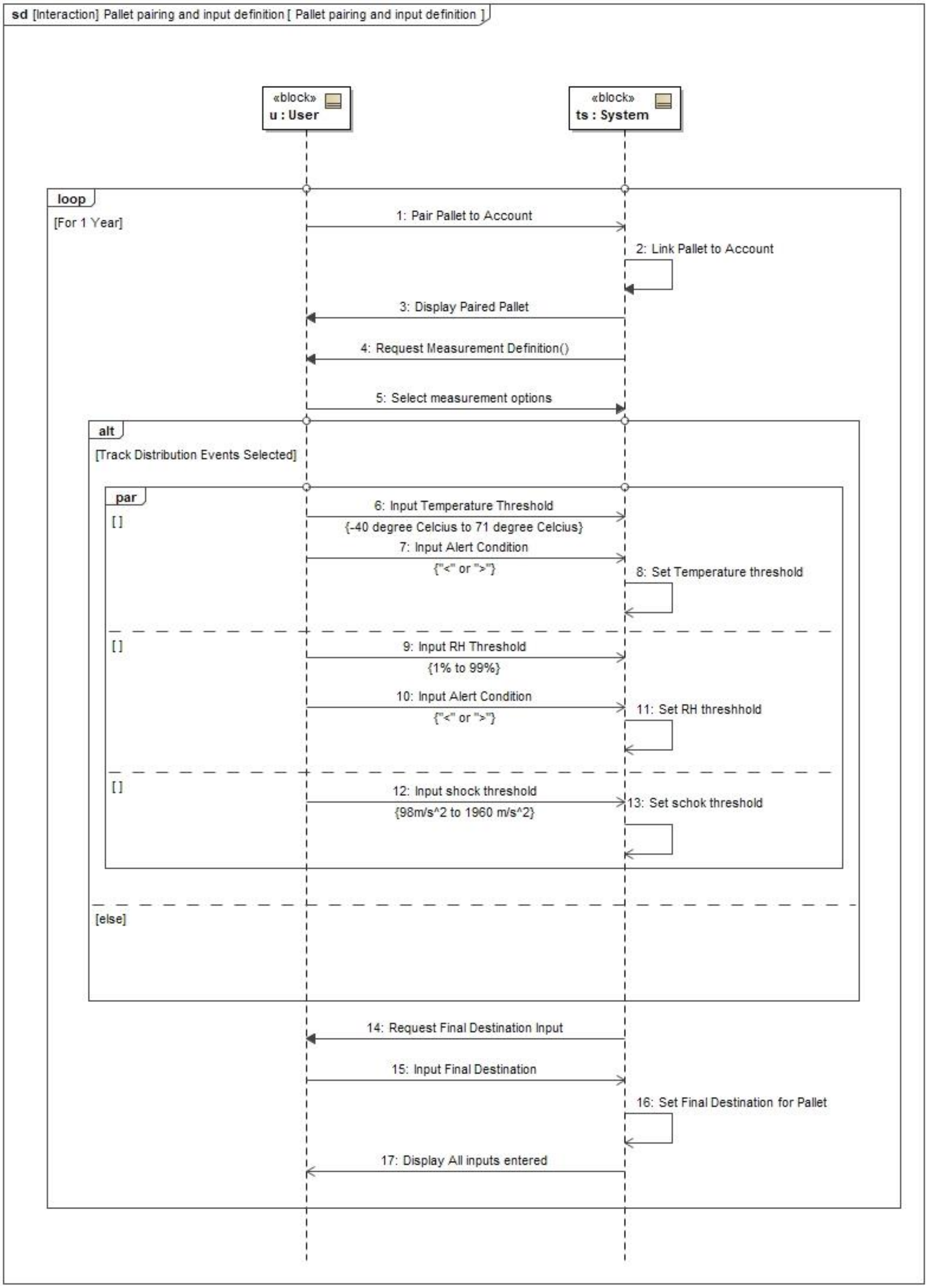

Figure 30. Pallet Pairing and Input Definition.

Figure 30 shows the formal modeling of the use case “Pallet pairing and input definition”, as a sequence diagram. Sequence diagrams depict the interactions that occur between different participants as a sequence of message exchanges. In this case, the diagram shows the message exchanges that take place when the user defines certain parameters for the operation of the system. The first interaction shown goes from the user to the system and consists of a signal by which the user indicates to the system that a specific pallet must be linked to a shipment in its account. The system then assigns the chosen pallet to that user’s account and displays back a message to the user confirming that the pallet has been paired.

Once the pallet is linked to the user’s account, the user defines certain input parameters that are needed for the operation of the system. To begin with, the system gives an option to the user to select the type of measurements that are intended to be collected. This can be understood by looking at the use case diagram shown in Figure 29. As the diagram shows, the first options are “record vibration profiles” or “record distribution parameters” in which case the user is given the option to select what parameters are to be recorded. The third option is “track distribution events.” For this, thresholds must be entered to the system, specifying which distribution events are to be tracked. “Location tracking” is the fourth option given by the system. This approach allows the user flexibility in selecting what needs to be measured in accordance with their particular needs. Later in this document the significance of those inputs to the system will be explained in greater detail.

The pallet pairing interaction must happen before all other interactions. The diagram shows also that if the option “track distribution events” is chosen, then there are three interactions that can occur in any order depending on what was selected. In the diagram, this is modeled through the operand “parallel” which indicates that the interactions within it can occur in any order. The operand “alt” indicates that the interactions within it are conditional, in this case by whether or not the user selected the option “track distribution parameters.” In addition, all of these interactions are happening within a loop cycle of one year. This indicates that the lifetime of the system has been established as one year. This is true for all the sequence diagrams presented in this section.

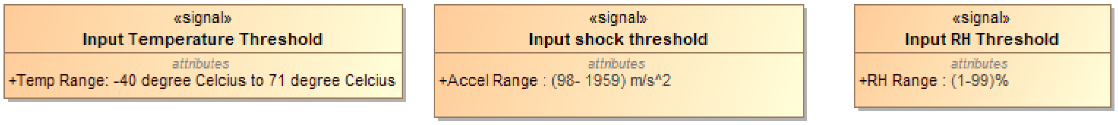

Figure 31. Threshold Input Requirements.

Figure 31 shows the threshold input requirements that the user must specify to the system. The requirements show the range of valid inputs that the user can enter. If they try to enter a value outside these ranges for each specific parameter, the system will not accept it.

4.2 Distribution parameters recording

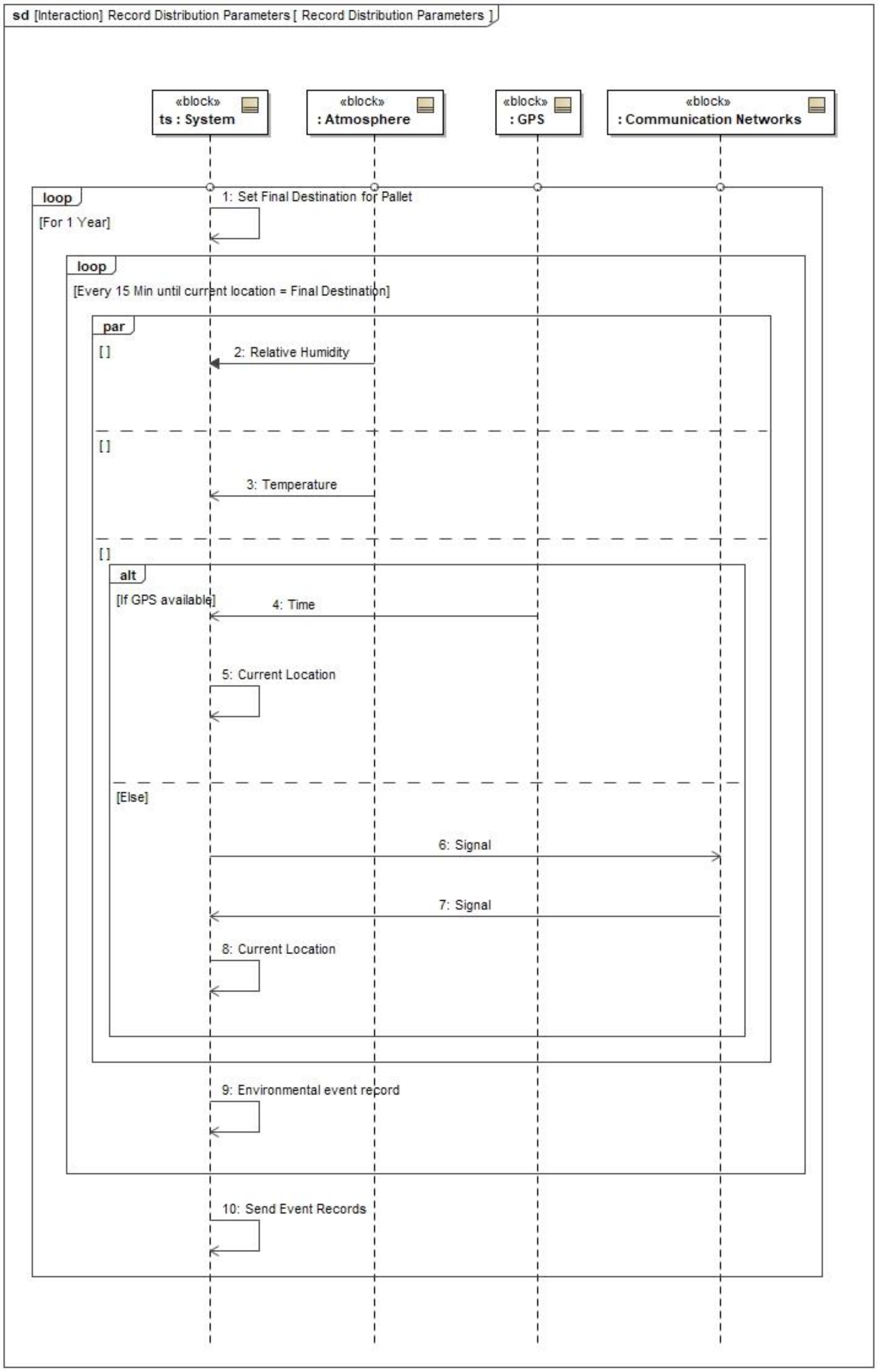

Figure 32. Record Distribution Parameters.

Figure 32 shows the sequence diagram for the use case “Record Distribution Parameters”. The interactions that occur in this use case go on for one year, which, as stated before, has been established as a reasonable lifetime for the system. Within this loop, the interactions in the system happen every 15 minutes from the moment that all inputs have been introduced by the user until the shipment reaches its final destination; thus, the specification in the cycle that states “until current location = final destination.” Every 15 minutes the system captures the temperature and relative humidity in its immediate surroundings, and determines its current location. It records this data as an environmental event and sends this event record to the cloud.

The parallel operand in the diagram shows that the collection of the environmental parameters, and the determination of the current location happens at the same time, followed by the sending of the recorded event. The operand “Alt” in the diagram which stands for “alternative”, indicates that the determination of the current location can be done either by an interaction with the global positioning system, or with communication networks. If GPS is available, then the location is determined using GPS; otherwise, the system will use communication networks to triangulate its location. This backup procedure is in place due to the fact that most unit loads and pallets travel inside metallic containers, through which getting a GPS signal is more difficult (Link Labs, 2018).

4.3 Distribution Events Tracking

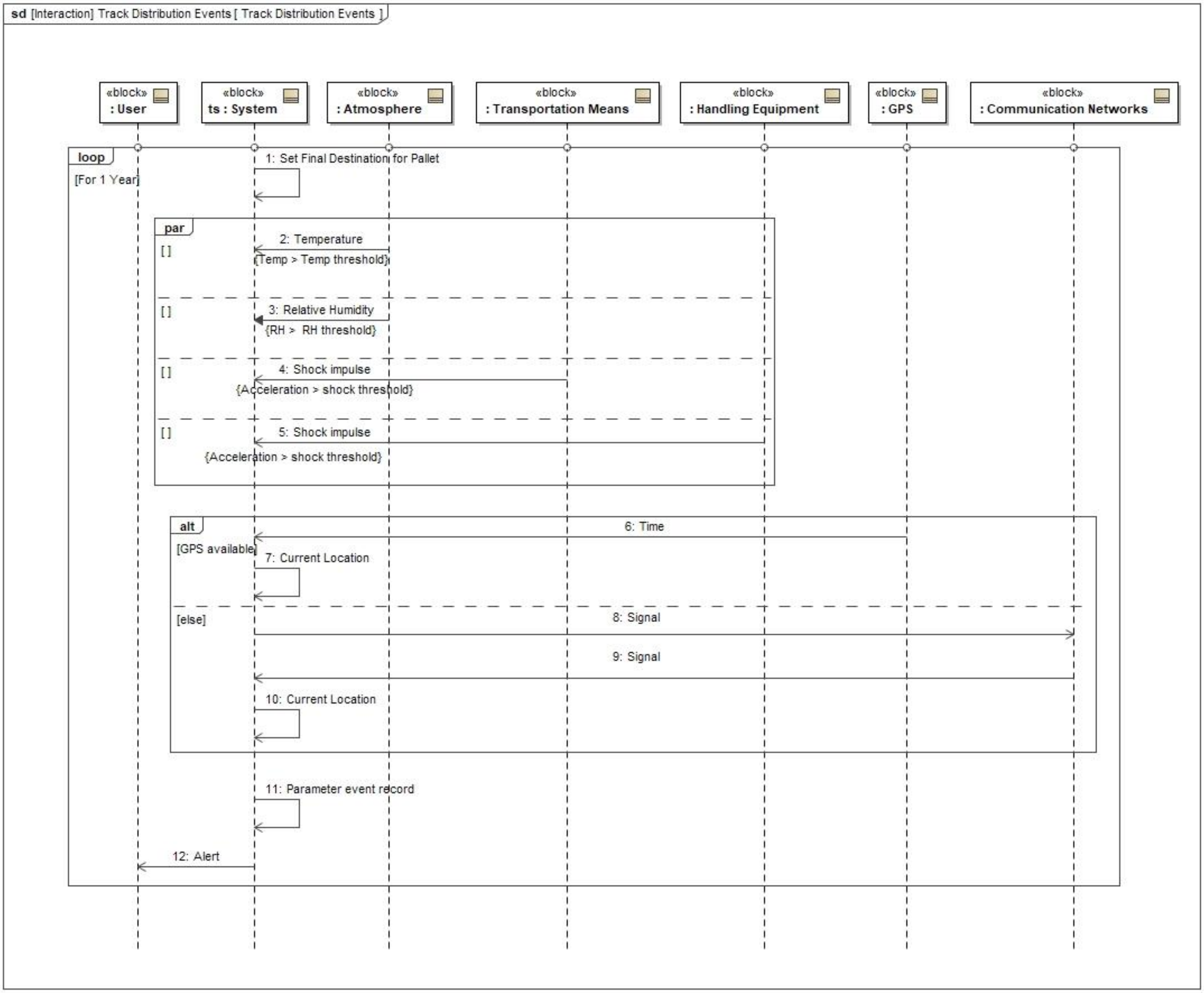

Figure 33. Distribution Events Tracking.

Figure 33 shows the sequence diagram for the use case “Tracking Distribution Events.” The sequence of interactions is triggered when the user has entered all the inputs into the system. Through the parallel operand (par), the diagram indicates that four interactions can occur in any order. And, the system will be basically waiting until any of the parameters exceed the predefined thresholds that the user has entered. When this happens for temperature, relative humidity, or shock, the system updates its current location, registers the parameter event record, and sends an alert message to the user warning them that one of the distribution parameters is moving out of the thresholds that were established for the shipment.

It is important to notice that the frequency of these interactions is dependent on the thresholds defined by the user. It is up to the user to specify these values according to their particular application, in relation to the levels of temperature, relative humidity, or shock that are considered a threat to the integrity of the product being shipped or the unit load’s stability.

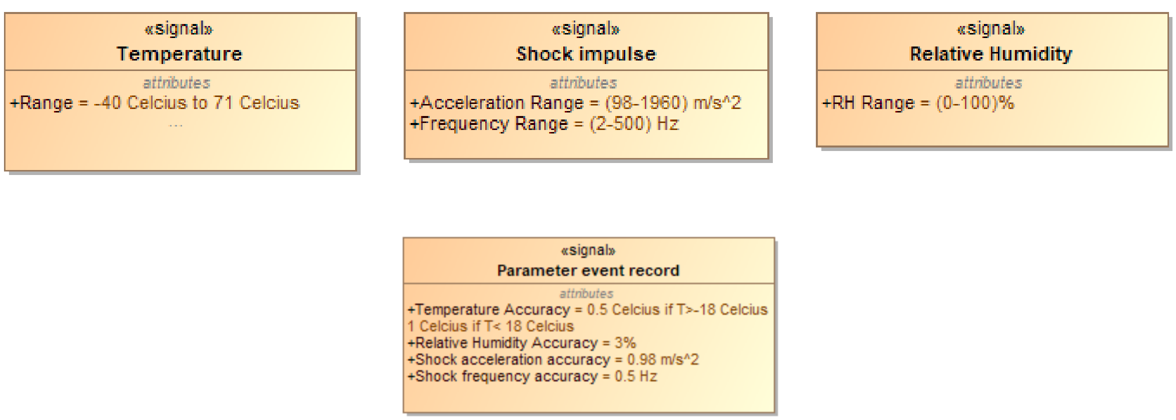

Figure 34. Functional Requirements for Sensing Capabilities.

Figure 34 shows the requirements for the sensing capabilities of the system. “Temperature”, “shock impulse” and “relative humidity” requirements depict the range of values that the system must be able to operate in and be able to sense; whereas, the “parameter event record” shows the accuracy that such measurements must have. These requirements also apply for the use case “record distribution parameters” shown in Figure 32.

4.4 Vibration Profiles recording

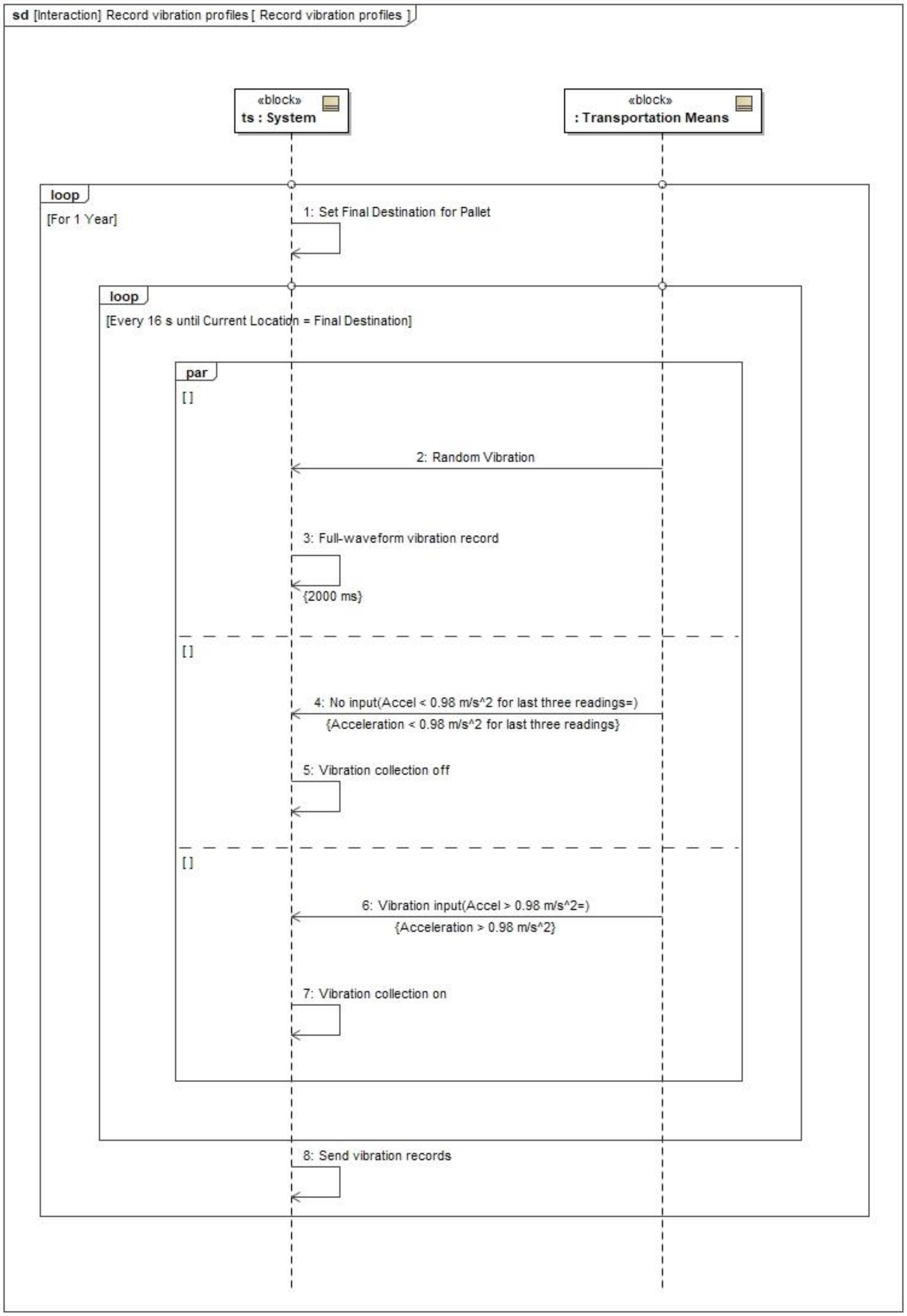

Figure 35. Record Vibration Profiles.

Figure 35 shows the sequence diagram for the use case "record vibration profile." In this, a sequence of interactions is triggered once the user has entered all inputs into the system. From this point forward, the system collects data every 16 seconds for 2000 milliseconds, which means that there will be 2000 data points that measure acceleration and frequency until the current location equals the final destination location. This constraint comes from the fact that it is necessary to capture one eight of the trips' vibration in order to get a statistically representative vibration profile (Rouillard & Lamb, 2008).

It is important to note that trucks are moving intermittently during trips for traffic, or other types of stops. During these times when trucks are not moving, vibration data is not relevant. It is actually detrimental to good characterization of a trip to include these periods of non-motion, as it would cause the vibration profile to be underestimated. This is why, in the model, a rule has been included that when the acceleration for three readings in a row is below 0.98 m/s^2, the vibration collection is turned off. It is turned back on again once an acceleration reading beyond 0.98 m/s^2 is captured by the system.

Another way to represent this behavior through modeling is with the state machine diagram shown in Figure 37. The state machine diagram depicts different states in a system and the transitions from one state to another one. In the case of vibration recording, the system has two states, "vibration data collection on" and "vibration data collection off." Figure 37 shows that the default state of the system is "vibration data collection off." There are two conditions that must be met in order for the system to transition to "vibration data collection on". These conditions are, first, that all of the required inputs have been entered into the system by the user, and second, that the system senses an acceleration higher than 0.98 m/s^2. Once the system is in the state "vibration data collection on", there are two kinds of transitions that can occur, either the system senses no input, which is defined as acceleration readings below 0.98 m/s^2 for three consecutive times, or the current location is equal to the final destination.

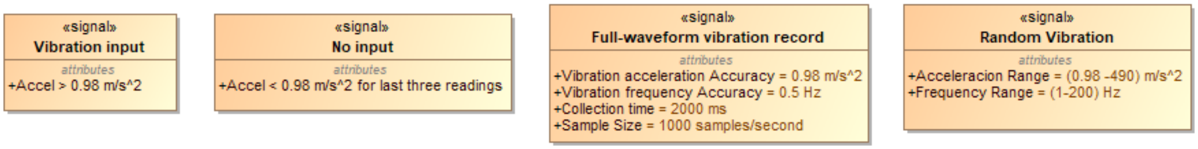

Figure 36. Functional Requirements to Measure Random Vibration.

Figure 36 shows the requirements that the system must meet in relation to random vibration measurement. "Vibration input" and "no input" requirements specify the conditions necessary for such signals to occur. The "random vibration" requirement specifies the range of frequency and the acceleration that the system must be capable of functioning in, and to sense. Finally, the Full-wave form vibration record specifies the accuracy that the measurement must have, as well as the duration of the measurement and the number of measurements that must be taken during such duration.

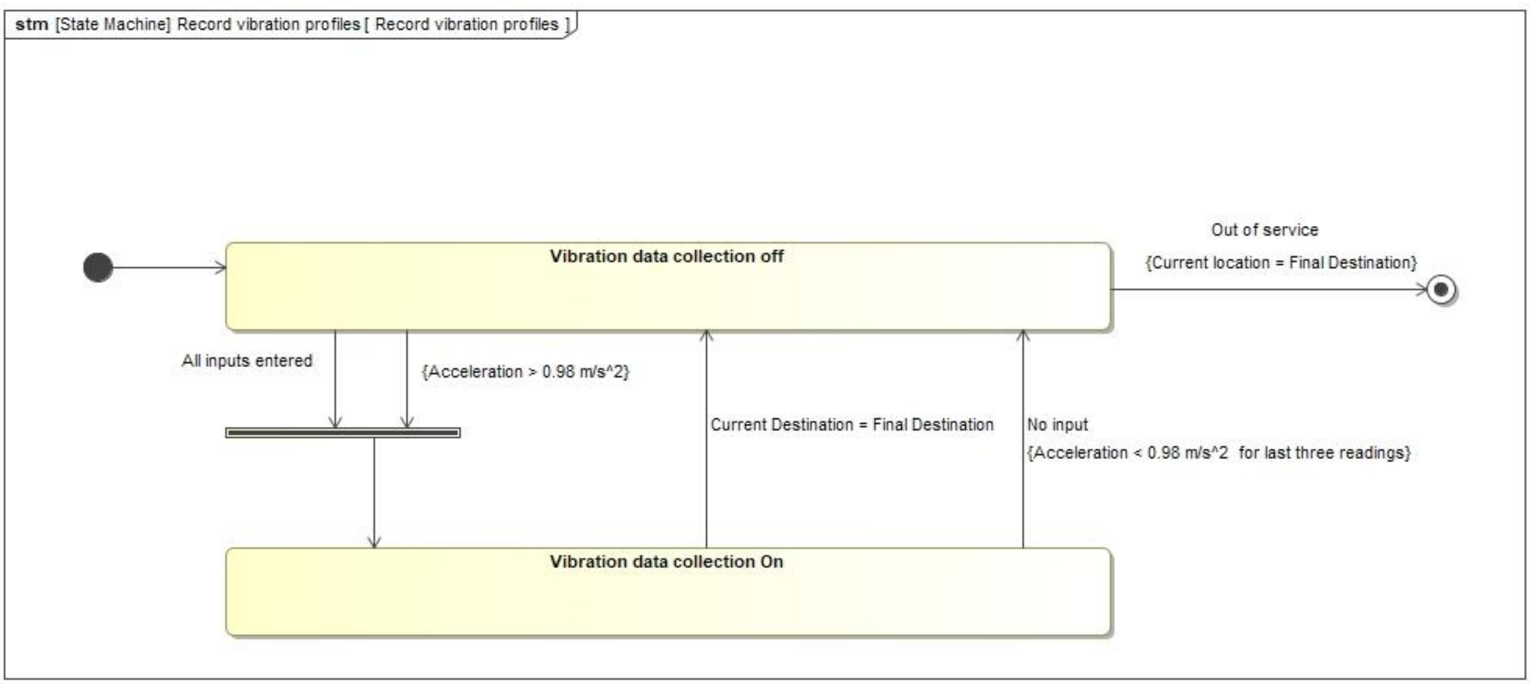

Figure 37. Record Vibration Profiles State Machine Diagram.

4.5 Distribution Parameter monitoring

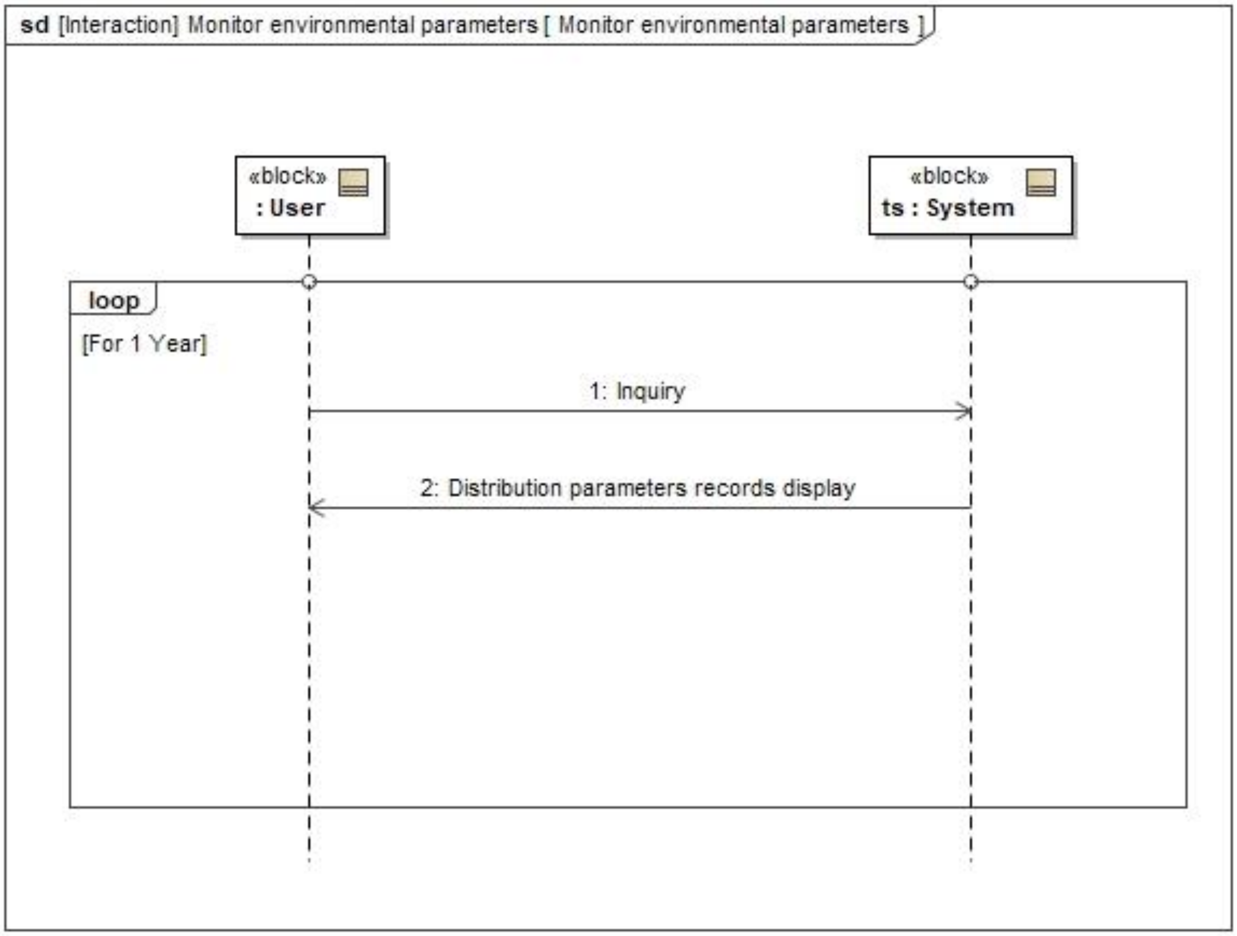

Figure 38. Monitor Environmental Parameters.

Figure 38 shows the simple interactions that occur for the use case "monitor environmental parameters." The user poses an inquiry to the system in order to see the data that the pallet has collected on its shipment, and in return, the system provides a display with all the recorded data that was gathered for the shipment.

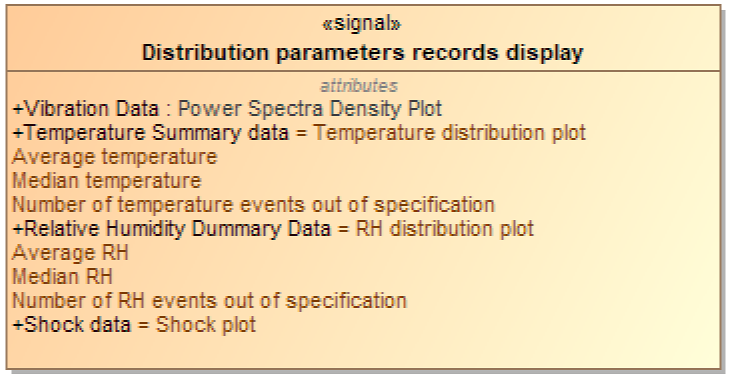

Figure 39. Display Requirements.

Figure 39 shows the requirements that the system must meet concerning the display of recorded data to the user. The requirements establish the format for the data given to the user for each parameter.

The frequency of data collection, as well as the range of values that the system needs to be able to cope with, is established in accordance with data collection standards for distribution conditions as prepared by the International Safe Transit Association (ISTA). ISTA is an organization dedicated to the development of testing protocols and standards used to help ensure the protection of products in the global distribution environment, presented in Table 5.

Table 5. Distribution Parameter Ranges and Accuracy (International Safety and Transit Association, 2018).

<table>
<tr><th rowspan="2">Parameter</th><th colspan="6">Requirement</th></tr>
<tr><th colspan="2">Accuracy</th><th colspan="3">Range</th><th>Sample recording rate</th></tr>
<tr><td>Temperature</td><td colspan="2">• ±1 °F (±0.5 °C) ≥ 0 °F (-18 °C)
• ±1.8 °F (±1.0 °C) < 0 °F (-18 °C)</td><td colspan="3">Min -40°F (-40°C) Max 160°F (71 °C)</td><td>15 minutes</td></tr>
<tr><td>Humidity</td><td colspan="2">±3%</td><td colspan="3">Min 0%
Max 100 %</td><td>15 minutes</td></tr>
<tr><td rowspan="2">Shock</td><td>Acceleration</td><td>Frequency</td><td>Acceleration</td><td>Frequency</td><td>Record time</td><td rowspan="2">Does not apply</td></tr>
<tr><td>0.98 m/s^2</td><td>0.5 Hz</td><td>(98-1960) m/s^2</td><td>(2-500) Hz</td><td>2000 ms</td></tr>
<tr><td rowspan="2">Vibration</td><td>Acceleration</td><td>Frequency</td><td>Frequency</td><td>Frequency</td><td>Record time</td><td rowspan="2">67 seconds</td></tr>
<tr><td>0.98 m/s^2</td><td>0.5 Hz</td><td>0.5 Hz</td><td>(1-200) Hz</td><td>2000 ms</td></tr>
<tr><td>Location</td><td colspan="2">Standard GPS accuracy</td><td colspan="3">Does not apply</td><td>15 inutes</td></tr>
</table>

5. System Architecture

The purpose of the following proposed functional, and physical architectures is to establish a set of guidelines that serve as reference for the for the design and development of a system solution for the problem formulation presented in the operational concept.

5.1 Functional Architecture

The structure of the system functions is presented in Figure 40 and shows the hierarchy levels between the functions that the system performs. The main function of the system is to track distribution conditions. This is subdivided in sub-functions that must be performed in order to achieve that main function. In this case, the sub-functions are labeled “Track Distribution Events”, “Record Distribution Parameters,” “Display Data,” and “Record Vibration Profiles,” which are subsequently divided into other sub-functions. Three of these initial sub-functions are described in greater detail from Figure 41 to Figure 43.

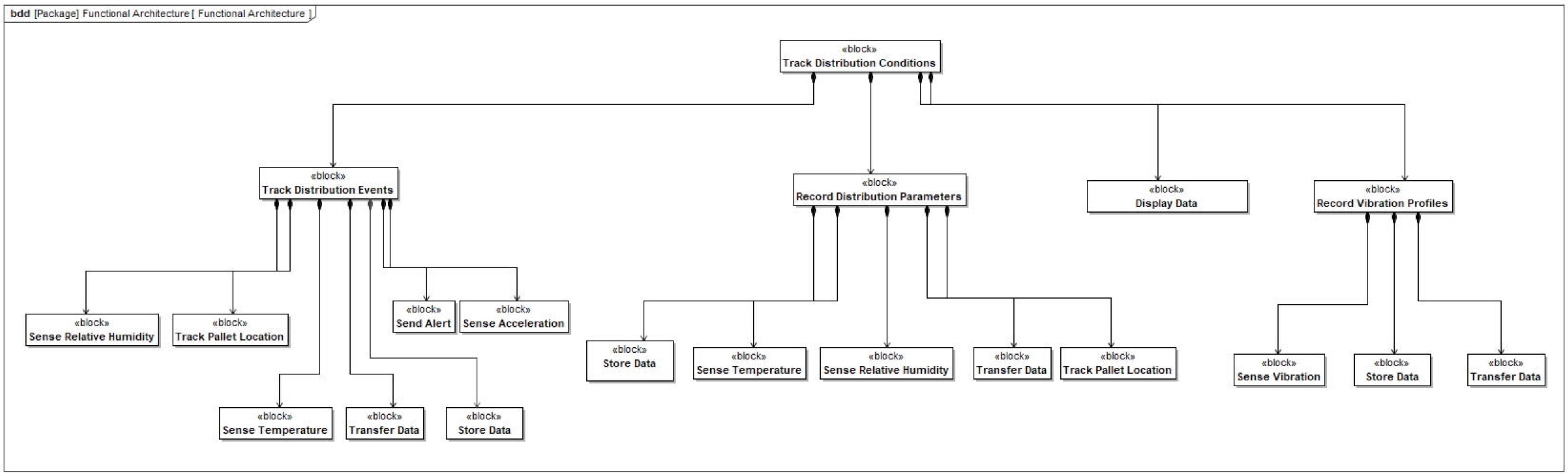

Figure 40. Functional Architecture.

5.1.1 Track Distribution Conditions

Figure 41 shows a functional block diagram that depicts the functions necessary to achieve the main system function which is "track distribution conditions." The entire functionality of the system can be characterized by three inputs and one output. In essence, the system receives inputs from the environment, in this case categorized as "environmental input," "vibration input" and "exceeded thresholds". This last function is any environmental input that exceeds user's defined thresholds. The system then turns these inputs into a main output, called "supply chain conditions," which provides the user information of interest.

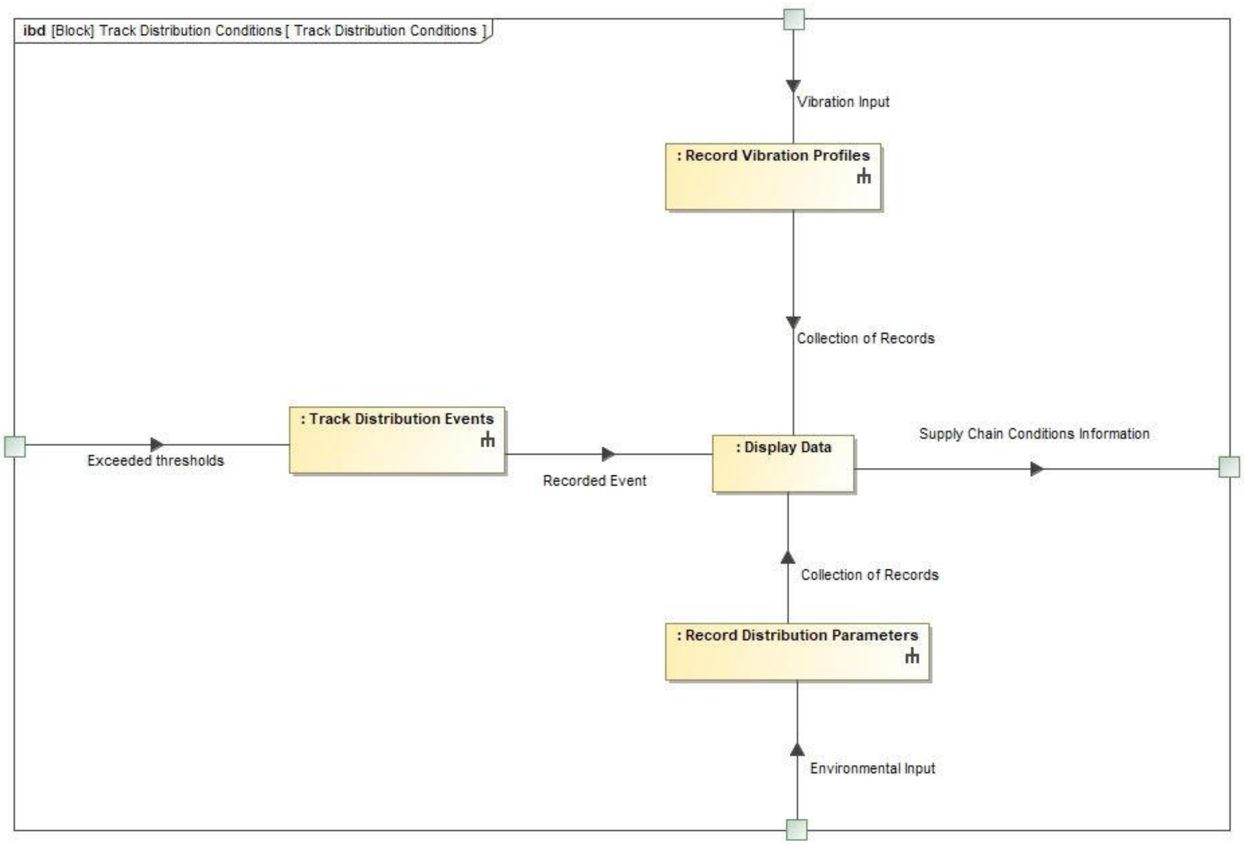

Figure 41. Functional Block Diagram for Tracking Distribution Conditions.

5.1.2 Track Distribution Events

Figure 42 shows a functional block diagram that depicts the sub-functions necessary to achieve the "track distribution events" function. This function is characterized by five inputs, "temperature," "relative humidity," "signal," "time," and "shock impulse," and two outputs, called "alerts" and "parameter event record." The function "track pallet location" has two inputs, given that it can be performed by using GPS signals ("Time"), or triangulation using other communication mechanisms ("Signal").

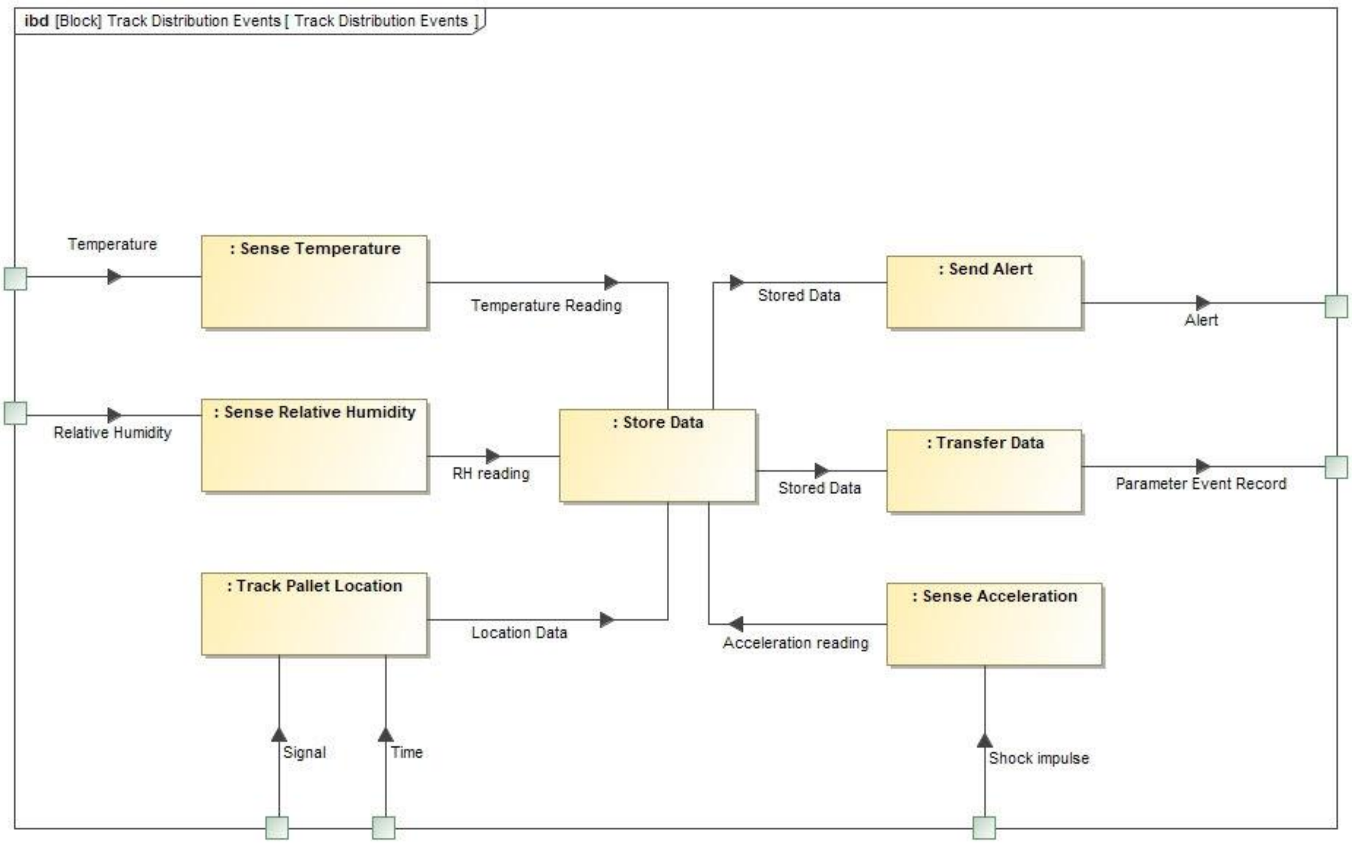

Figure 42. Functional Block Diagram for Tracking Distribution Events.

5.1.3 Record Distribution Parameters

Figure 43 shows a functional block diagram that depicts the sub-functions necessary to achieve the "Record Distribution Parameters" function. The diagram is very similar to the one showed in Figure 42, except, there are no functions to sense acceleration, nor send alerts.

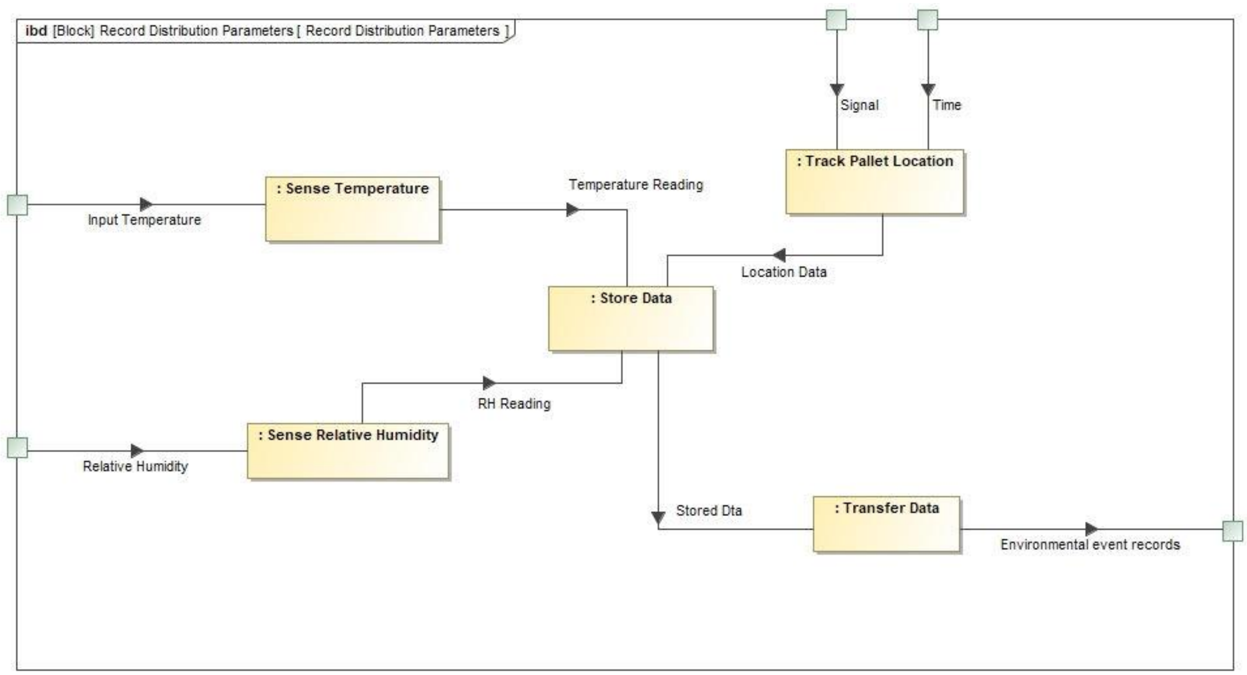

Figure 43. Functional Block Diagram for Record Distribution Parameters.

5.1.4 Record Vibration Profiles

Figure 44 shows a functional block diagram that depicts the sub-functions necessary to achieve the "Record Vibration Profiles" function. This function is characterized by one input, "Vibration Input," that the function transforms into "Vibration Records" after recording, storing, and transferring data.

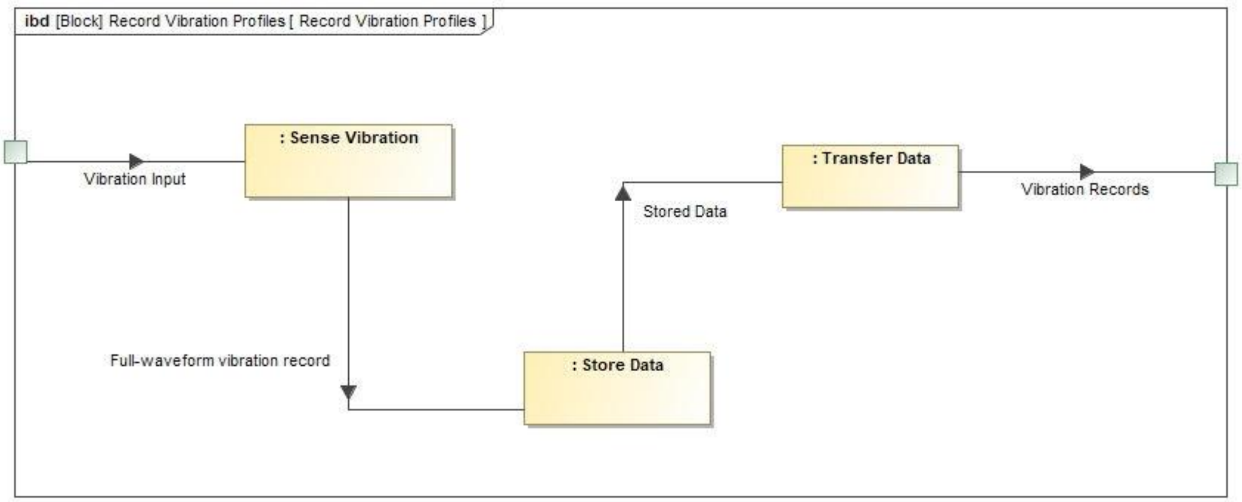

Figure 44. Functional Flow Diagram for Record Vibration Profiles.

5.2 Physical Architecture

The structure of the system's constitutive elements is presented in Figure 45. From a physical point of view, the system is composed of two basic elements: the smart sensor and the software platform. The smart sensor includes the components that make possible the execution of the functions detailed in the previous sections. The software platform is the component to which data is transmitted and which conveys information to the user. The inputs and outputs of the physical system and the relationships between them are described in the functional block diagram in Figure 46.

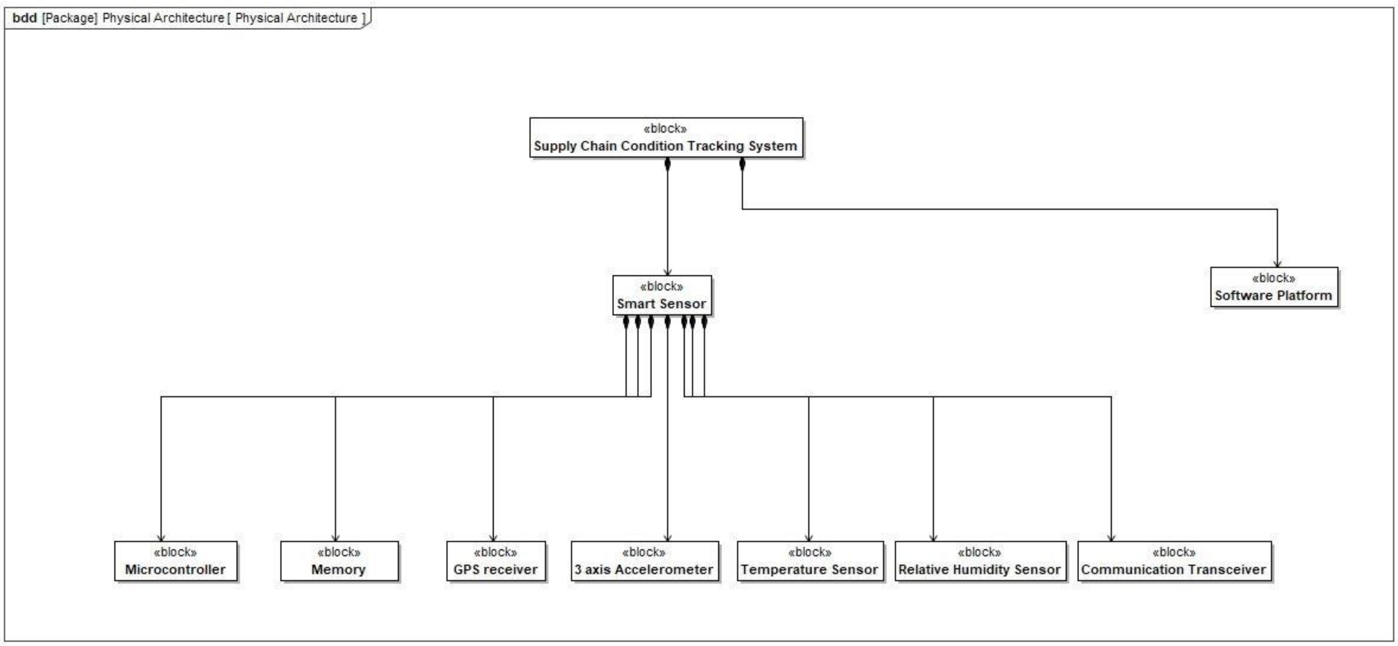

Figure 45. Physical Architecture.

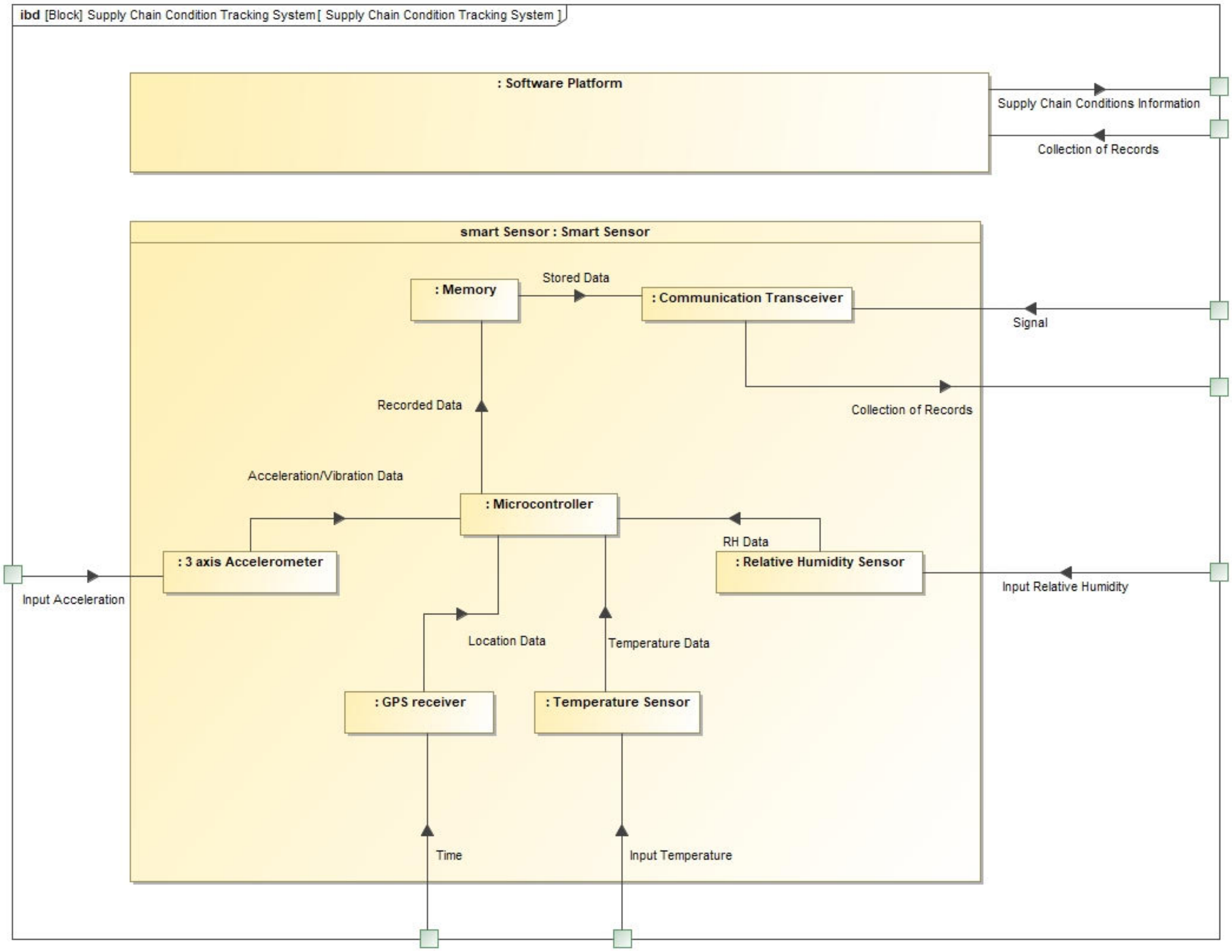

Figure 46. Functional Block Diagram for the Supply Chain Condition Tracking System.

C. CHALLENGES FOR THE IMPLEMENTATION OF THE PROPOSED OPERATIONAL CONCEPT.

1. Security for IoT Applications

Addressing security concerns in the context of Internet-of-Things applications is essential ensuring the commercial long-term success of its implementation by multiple stakeholders in different industries (Miorandi et al., 2012). Further implementation and expansion of IoT applications in the industry depends on finding solutions that comprehensively address privacy, security, efficiency, and scalability concerns (Siegel, Kumar, & Sarma, 2018).

Widespread adoption of very capable, low-cost hardware for IoT has created several security vulnerabilities that will continue to represent limitations to the IoT technology until validated solutions are universally in place (McGinthy, 2019). Furthermore, developers are rushing to release products to the market as fast as possible in order to capture market share, and this has led to security coming as an afterthought, rather than being included as a design priority (McGinthy, 2019).

The IoT environment imposes specific constraints on developers from a security standpoint. Many IoT devices are designed to be physically small, to run on low power and to have the minimum processing capacity required to function. Adding security capabilities to these devices becomes a technical challenge; security requires additional storage capacity, more energy, and more computation power (Babar, Stango, Prasad, Sen, & Prasad, 2011).

Measures to address security concerns, like cryptography convey greater costs to IoT applications due to the necessity of processors with higher memory and speed (Siegel et al., 2018). Furthermore, traditional security solutions are designed for desktop-type computers with high computational power and do not scale down efficiently to the IoT constrained infrastructure (McGinthy, 2019).

The three basic functional layers that have been discussed before (object, communication network, and application) create many attack vectors in cyber-physical systems. Each layer is subject to vulnerability and potential attack. As devices communicate among themselves, with the cloud and with other objects across the layers, every communication should be secured. This protection provides users with confidence in the system's functionality (Alaba, Othman, Abaker, Hashem, & Alotaibi, 2017; McGinthy, 2019). Table 6 shows the different types of attacks to which the three functional layers of an IoT system can be subject.

Table 6. Potential Attacks for Internet-of-Things Technology.

Layer	Types of attacks	Description
Hardware	Tampering	An attempt, effort or action directed to compromise the physical integrity, or the data associated with a node or device (Caddy, 2011; Robertson & Riley, 2015)
	Exhaustion of resource	Attacks oriented to drain the energy of targeted IoT nodes. This might take place by sending high volumes of data to a node and making them respond or re-transmit data.
Network	Denial of service	This type of attack prevents legitimate data traffic to reach its destination by usually transmitting large amount of data to the target destination, therefore consuming the bandwidth available (Keromytis A.D, 2011).
	Man-in-the-middle	The goal of this type of attack is to seize and control the communication channel, potentially altering the content of the messages transmitting between nodes (Alaba et al., 2017).
	Eavesdropping	The goal of this type of attack is to extract data from the flow of information between two communicating nodes (Roman, Zhou, & Lopez, 2013).
Application	Cyberattacks	Attacks directed to a website hosting the application where data from the field is integrated (Babar et al., 2011).

Literature suggests several attributes that a system must have in order to cope with the risks presented by various types of attacks described in Table 6 and to provide security and trust in IoT systems. According to the international standard ISO/IEC/ IEEE 24765, security is defined as *the "degree to which a product or system protects information and data so that persons or other products or systems have the degree of data access appropriate to their types and levels of authorization"* (ISO/IEC/IEE, 2017).

One of these suggested attributes is confidentiality of data. This means that data can be accessed and modified only by authorized users and objects for which an access control mechanism and an object authentication process are necessary (Miorandi et al., 2012). Authentication aids to ensure that the data collected from and stored about an object is what is supposed to be (Roman et al., 2013).

In a network of sensor nodes, authentication verifies the identity of a node and confirms that the node is legitimate. A method using three alternative protocols to assist in the authentication process intended for IoT systems is proposed by McGinthy (2019). It is called "specific emitter identification" and is based on artificial neural networks; however, its performance has not been validated. The edge nodes in a network will not be capable of running these algorithms, which limits this approach's ability to be implemented in some of the elements of the IoT infrastructure, like gateways and other access points. The authentication problem in IoT sensor networks remains a technical and research challenge.

A key derivation function for IoT environments is also proposed by McGinthy (2019). This function produces variable length keys from an already distributed larger secret key to be used in encryption processes to secure data communications. This aids in the prevention of attacks like man-in-the-middle and eavesdropping.

Another critical aspect of securing IoT systems and applications is to prevent tampering. Recent events have made evident the huge risks that this kind of attack poses to private companies and even national security (Robertson & Riley, 2015). According to McGinthy (2019), physical security is something that must be tackled from the manufacturing stages of the hardware components, and this requires a good understanding of suppliers and supply chain risk management.

2. Energy Resourcing for IoT Applications

The application of IoT in industrial settings presents particular constraints in terms of energy utilization. This poses a challenge to the adoption and scalability of IoT systems, which must exhibit adequate levels of reliability in order to satisfy user needs. This means that IoT systems must be capable of meeting system requirements throughout their lifecycle and assuring that they have enough energy to operate is vital to proper functioning.

The energy consumption of IoT devices also relates to their environmental impact. One of the promises of IoT technology is that more data allows for greater optimization and efficiency, which will have a positive impact on the environment by saving resources (Cooper, 2016). For example, the proposed operational concept presented in this thesis enables packaging optimization, which saves material resources, fuel consumption, and less product waste. On the other hand, IoT devices require energy to function. The more sophisticated their capabilities, the more energy they consume. Furthermore, an increasing number of deployed IoT devices eventually means more electronic waste, which is detrimental to the environment (Mukhopadhyay & Suryadevara, 2014).

There are three ways in which an IoT system can meet its energy requirements. The first is having a battery that can provide enough energy for its entire lifecycle without the need for charging. This might be the hardest solution to achieve, because it implies storing large amounts of energy in very reduced spaces. The second option is to have an IoT system that incorporates a mechanism that collects energy from its environment; called energy harvesting. The third way to achieve energy reliability is to wirelessly transfer energy to the system in a way that does not require direct manipulation of the system, which is important especially when the system is embedded in other systems or is inaccessible.

2.1 Energy Harvesting

As energy becomes a limitation, one option is to make devices capable of providing themselves with energy from their surroundings (Kamalinejad et al., 2015). One option is to produce energy through vibration, a method that is called vibration energy harvesting uses technologies like electromagnetic induction and piezoelectric fibers technologies. Although in theory, every vibration could be converted into electricity, when the focus is to generate enough power to fuel a functioning sensor, the vibration should have the following characteristics(Revibe Energy, 2018):

- A steady vibration is preferred over random shocks.
- A frequency that is dominating.

Revibe Energy is a company that manufactures various models for vibration harvesting as well as customized solutions. From left to right, Figure 47 shows the models A, Q and D developed by this company, which are all small in size, the biggest being model A 155mm x 53 mm x 17 mm and all weighting less than 300 g (Revibe Energy, 2018).

Figure 47. Examples of Vibration Energy Harvesters (Revibe Energy, 2018).

Energy harvesting in distribution packaging domain was the topic of research for Berry (2016), who explored the idea of placing a tier sheet to work as a triboelectric energy harvester within a unit load, taking advantage of the vibration movements that takes place between a unit load's layers to produce energy.

According to Berry (2016), a triboelectric energy harvester is a device that "uses the principle of contact electrification between two oppositely charged materials and can capture the electrical charge transferred between them." The results of this study showed that the proposed approach is capable of powering a battery of up to 5 V, which means that it could individually power a temperature / relative humidity sensor, and a GPS module, but not vibration data recorder, as that requires a power supply of 9V. The principle used by Berry (2016) is promising, and its application to IoT systems an opportunity for further research.

2.2 Wireless Energy transfer

Basically, wireless charging technologies are divided into non-radiative coupling-based and radiative, radiofrequency-based charging, as represented in Figure 48.

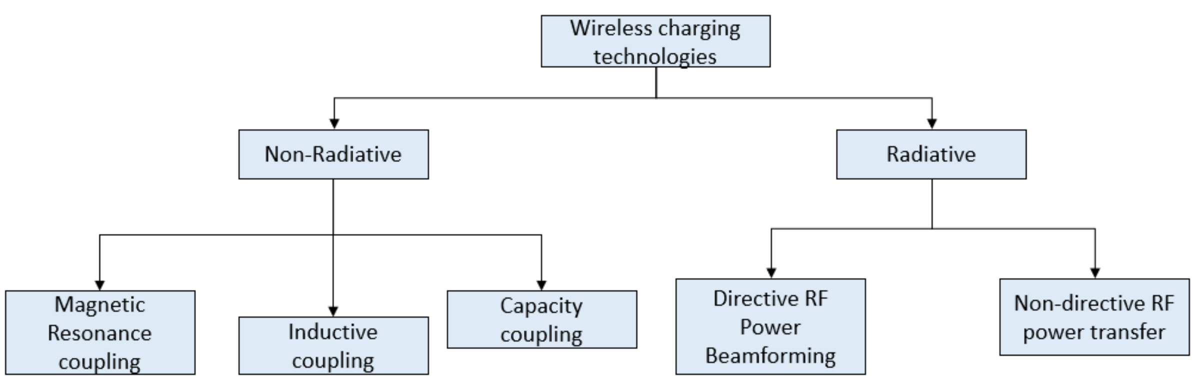

Figure 48. Classification of Wireless Charging Technologies (Lu, Wng, Niyato, Kim, & Han, 2015).

Capacitance coupling and directive RF beam transfer both convey disadvantages that limit their applicability for energy transmission. Capacitance coupling requires large device area, which is scarce for small devices, and directive RF beam transfer requires a direct line of charging. Inductive coupling and magnetic resonance coupling both work for applications that involve energy transferring within close distances, like cellphone charging. These coupling technologies are considered safe for humans but are not suited for mobile applications. In addition, inductive coupling requires close alignment between chargers and has a heating effect. Non-directive RF power transfer, on the other hand, is well-suited for mobile applications, and it can transfer energy from tens of meters of several kilometers, but it is not safe for humans when the density exposure is high (Lu et al., 2015).

3. The System Power Life and Service Life.

In the models showed in section B.3, the interactions occur within a loop that states, “For 1 Year.” This indicates that the power life for the system is expected to be at least 1 year. The system service life or lifetime is the amount of time for which the system is expected to function before being phased-out. The battery life is the time the system is expected to function before without need for being recharged.

The power life of the system is related to the lifetime of the pallet, which in practice is highly variable depending on the characteristics of the pallet, the rigorousness of the material handling environment, and the intended uses of the pallet. For this operational concept, a typical specification for a reusable pool pallet was introduced into the Pallet Design System (PDS) software in order to obtain a predicted service life under average pallet handling and treatment, medium-duty loads, and a dry environment. The PDS software is a tool for pallet design, structural analysis, and durability prediction. It predicted 16 cycles of service life for the entered specifications of a reusable pool pallet. A cycle is understood as the sequence of steps that a pallet experiences from the point where products are unitized on top to the point where the unit load is depalletized and the pallet is directed out to be reused.

Sixteen cycles of services for a pallet could be very variable in terms of how long it takes for those cycles to be completed, depending on the type of industry, type of material handling system, and type of logistic system. For example, a study by William and Strobel (1973) as cited by (Cao, 1993) looked into how pallets were used in 16 different handling systems, and determined that for an average pallet, 1 cycle is the equivalent to 0.12 years of use, which means that 16 cycles would be the equivalent to 1.92 years. Another study by Procter & Gamble Co. (1989), focused specifically on the groceries industry, indicated that one cycle is equivalent to 0.167 years of use, which means that 16 cycles is equivalent to 2.67 years. This highlights the variability of service life for pallets used in different industries.

For the purpose of modelling in this work, it was considered that one year of life expectancy is a reasonable expectation. However, the important point to consider here is the principle that the desired life expectancy of an IoT system that travels in the pallet must consider the purpose of the pallet, and the environment in which it operates.

This approach for the definition of the power life of the proposed system is based on the assumption that if the power life of the system is shorter than service life of the pallet, it will require the system be extracted from the pallet before the pallet is due for disposal, which is unpractical considering the nature of pallet repair operations.

4. The Location of IoT Infrastructure in the Pallet.

There are two principles that must guide the decision of where to locate IoT infrastructure in a pallet. First, it must be located in a place that provides a good degree of protection, and second, it must be placed in such a way that nothing causes communication problems.

Pallets are subjected to rough handling by forklifts, and other handling equipment during loading, unloading, and storing processes during distribution. Those elements in the pallet that directly interface with the material handling system are more vulnerable to being damaged. These are elements, such as lead deck boards, bottom deck boards, the ends of stringers and blocks, sides of stringers, and stringer boards in block pallets.

Although no single element of the pallet is free from the risk of damage, the center of the middle stringer (on stringer pallets), and the center middle block (on block pallets) are the elements that are the least likely to be damaged. This was confirmed by Wallin, Strobel, Frost, & Stinson (1972); these authors found that for the most frequent type of damage to stringers, 90% of these damages occurred on the edge stringers, and only 10% on the middle stringer. The same study also found that the top deck end boards, which are on the outer part of the pallet were 350% more likely to get damaged than center board. All of this data reinforces the assertion that the center of the pallet is the place with least risk of damage. Looking at these two types of pallets, the middle center block in a block pallet is probably less likely to get damaged than the center of the middle stringer in a stringer pallet. Even though it is technically possible to install IoT infrastructure in stringer pallets, the practical use of pallets suggest that it is more convenient to enable block pallets with IoT capabilities, as these are more robust, have a longer lifespan, and are more suitable for reusable applications. The second consideration is the ability of the infrastructure to communicate in a reliable way. The challenge with more sophisticated infrastructure is to be able to protect it while not affecting the reliability of communication.

5. Computation versus Communication for System Efficiency.

Within the field of research of distributed networks, the issues of computation versus communication in scalable systems has been given significant focus. The reconcilement of in-network computing and in-network communication with viable IoT architectures remains an important field of research (Shahid & Aneja, 2017). In the context of this project, this can be exemplified by looking at the problem of measuring vibration. In the model presented in Figure 35, it is shown that every time that the sensor collects data, it records 2000 points of intensity and frequency, so effectively, every record implies 4000 points. Collecting this much data every 16 seconds for 4 effective hours, for example, creates a considerably large data set. However, as shown in Figure 41, what is of interest to the user is a power spectra density plot, like the one presented in Figure 22. Thus, all the data collected can be summarized into a single chart. The question is whether it is better to transfer all the 3 600 000 data points collected in those four hours to someplace where the data is then summarized into one chart, or to process that data into the chart, and then just transmit the one chart. The technical answer to this question is beyond the scope of this project, but it is useful to point out these types of practical challenges that arise from the implementation of IoT systems. These are the types of things that need to be well sorted out in order to procure system reliability and achieve user satisfaction.

VI. CONCLUSIONS

- There is a need among industrial companies to avoid damages to their products during the distribution process, as well as to increase the visibility of the movement of those products as they travel along the supply chain. In order to satisfy these needs, it is necessary to gain insight into the conditions that are experienced in the field by products and their packaging. This can be achieved by having the capability to remotely measure and track temperature, relative humidity, shock, vibration, and location, as well as the ability to transmit this collected data wirelessly to the user.

- An operational concept of a system that uses Internet-of-Things (IoT) technology to capture data about the conditions in the distribution environment is proposed using a systems engineering framework that achieves the aforementioned data-collection capabilities to satisfy the needs of industrial companies related to the packaging and product performance during distribution. Leveraging on a systems engineering framework and model-based systems engineering is adequate for this application because it allows to address the complexity presented by the nature of IoT technology, so that the system developed is more likely to meet the requirements necessary to satisfy the user’s needs. Furthermore, the application of the systems engineering framework makes it possible to lay-out a clear value proposition for the adoption of a new technology, like IoT, in the field of distribution packaging and supply chain, so there is higher certainty that the new system will be responding to genuine user needs.

- The following challenges and research opportunities for the adoption of IoT in the field of distribution packaging and supply chain were identified:
    - Cyber-security concerns that relate to the integrity of the IoT network and the information exchanged between different nodes.
    - Energy constraints that originate from the size of the devices, which require further innovation in areas like battery capacity, energy harvesting, and charging capabilities like wireless energy transfer.
    - The most suitable location to install IoT infrastructure in a pallet is still to be confirmed with empirical experiments.
    - The selection or combination of in-network computation, and in-network communication also requires further experimental research to provide insight into the optimal strategies for different scenarios.

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VIII. APPENDIX

A.

Questions for potential users of the system.
Q1. What type of products does your company manufacture?
Q2. How are your products distributed to your customers?
Q3. What are the main distribution hazards present downstream your supply chain?
Q4. What type of information about your supply chain's distribution hazards is currently available to you for the packaging design process?
Q5. What information about the distribution conditions downstream the supply chain or about the conditions of your cargo would be valuable for your company to know on a continuous basis?