Towards a Generalized Value Stream Mapping and Domain Ontology to Support the Enabling of Industry 4.0 in Construction

by

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Abstract

Construction projects have temporary fragmented supply chains that face many challenges, such as lack of trust, inadequate knowledge management, and poor communication. These challenges led to poor performance in terms of low productivity, high cost, schedule delay, and poor quality. Construction is a conservative industry resists changes to its structure and adoption of technology and new management principles. The study aims to develop a value stream mapping and information management frameworks for construction projects. The developed frameworks can support the elimination of wastes and facilitate the integration of the construction supply chain, which ultimately reduce the project's cost and lead time. It can also support the current shift towards Industry 4.0, which targets the enabling of Construction 4.0. Surveys and interviews are conducted to determine existing tools to exchange information, the extent of value stream mapping (VSM) adoption, and the key performance indicators in Alberta. The results show Alberta's industry mainly depends on face-to-face discussions, phones, and emails to exchange information. The knowledge most likely stays at the individual levels and neither shared nor stored and poorly managed. This hinders knowledge capitalization, as well as the integration of the value chain network. Alberta's construction industry hasn't adopted lean management tools yet, and no common key performance indicators (KPIs) are established. Case studies are completed to implement VSM in procurement case studies. The results show traditional VSM can efficiently identify wastes in the current state of repetitive construction processes and eliminate them in future ones. The study proposed a new VSM framework for non-repetitive processes, which is more suitable for onsite construction activities. The framework is implemented in case studies. The results show significant improvements in terms of reducing wastes and the project's lead time. The construction industry lacks standard methodology for ontology development. The ontologies that have been developed in construction have a deficiency in a philosophical basis and built for a specific use, and for certain project types and phases. To support knowledge management, which can facilitate information flow in the construction supply chain, an ontology for construction knowledge is developed using the Basic Formal Ontology (BFO) structure, ISO 12006-2 recommendations, and input from industry experts. BFO is a mature upper ontology. It provides a framework to build a complete ontology based on philosophical basis. An ontology for the VSM framework is also developed using the BFO structure, so it can be integrated with the construction knowledge ontology. The developed frameworks can also support the industry's current efforts to promote more collaborative project delivery approaches.

Preface

This thesis is an original work by Mohammad Abdelghani. The research project, of which this thesis is a part, received research two ethics approvals from the University of Alberta Research Ethics Board, Project Name "Generalized Value Stream Mapping (GVSM) and Information Flow System (IFS) for Cross-Enterprise Project Management (CEPM) in construction", No. Pro00078004, Feb 20, 2018, and No. Pro00089508, April 30, 2019.

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Chapter 1: Introduction

1.1 Motivation

Construction is a major sector in the world economy, with approximately $11.4 trillion spent on construction-related goods and services in 2019, [1]. Regardless of the significant contribution to the economy, the *construction supply chain* (CSC) is the least integrated among all other major sectors, [2]-[3]. CSC lacks the integration along all project phases and collaboration among stakeholders, [4]. The construction industry has underperformed in terms of labour productivity and quality compared to other industries, [5]. The estimate of wastes in the construction industry starts at 55%, [6]. Labour productivity in manufacturing has approximately doubled since 1994, while in construction it has remained nearly flat, [7]. Construction performance has been suffering worldwide: 72% of the projects are delayed, 63% have cost overruns, significant rework, and low customer satisfaction, [8]. The construction industry has an opportunity to increase its productivity by five to ten times and enhance its value-added by $1.6 trillion USD per year by acting in multiple areas, such as reshaping design and engineering processes, changing contractual frameworks, improving supply chains, increasing onsite efficiencies, implementing digital technology and automation, training workforces, and adopting manufacturing production systems, [9]. Taking into consideration these areas, enabling *Industry 4.0* in construction can be an opportunity to overcome many challenges the industry has been facing.

The *Industry 4.0* concept emerged in Germany in 2011 as a vision for advanced manufacturing, [10]. It represents the fourth industrial revolution, which is based on the integration of information, communication, and industrial technologies, [11]. The first industrial revolution started at the end of the 18th century and was based on mechanical production driven by steam, [12]. The second industrial revolution started in the early 20th century and was led by mass production powered by electricity, [12]. The third industrial revolution emerged in the early 1970s and was driven by computers that supported automated production, [12].

Brettell et. al defined *Industry 4.0* as the decentralization of manufacturing to build a global system that shares resources to increase efficiencies and achieve customization, [13]-[14]. Such an integrated system can promote industrial specialization with higher resource utilization that can benefit all stakeholders, including consumers and producers. It can also help *small and medium enterprises* (SMEs) to access global markets and have the ability to compete with larger organizations, [14].

A broader definition of *Industry 4.0* is the promotion of digitization, customization, and information-led industries to increase operations' efficiencies and achieve a higher level of automation, [11]. Industry 4.0 has also been discussed in the context of the concepts and technologies that form its foundations such as *cyber-physical systems* (CPS), *Internet of Things* (IoT), *Internet of Services* (IoS), and *smart factories*, [15]. CPS is defined as the systems that connect the real and virtual worlds with the ability to cooperate, adjust, and progress, [16]. In the CPS world, every physical system has a virtual representation and vice versa, i.e. every virtual system has also a link to a physical one. The connection between the two worlds is viewed from communication, information, and control perspectives, [17]. CPS uses sensors and computing systems to capture, understand, and analyze the changes in the real world, then control it through smart decisions, [17]-[18]. IoT is a global network that connects devices using sensors, communication, and information management technologies such as *radio-frequency identification* (RFID) and *wireless sensor networks* (WSNs), [19]. RFID allows the transfer of information through wireless communications while WSNs use sensors to monitor and control systems, [20]. IoS emerged from the two concepts *Web 2.0* and *service-oriented architecture* (SOA), [21]. Web

2.0 has four major aspects: (1) web services that enable the communication between servers and web browsers, (2) social networking which allows the information to be available from multiple sources in different formats, (3) tagging that allows adding keywords to make the internet content searchable, and (4) web services that make web applications available to humans as well as machines, [22]. SOA is the design of information technology in a structured manner that allows applications and web services to be accessed simultaneously by many users, [22]. The smart factory concept represents the integration of machines and information management systems to achieve higher flexibilities and efficiencies in factories, [23].

Industry 4.0 technologies provide continuous communications not only between humans but also among machines themselves. This interaction establishes the need for new knowledge management systems which are called *knowledge management* (KM) 4.0, [15].

The construction industry adopted the *Industry 4.0* concept and called it *Construction 4.0*, [24]. One of the main aspects of *Construction 4.0* is information flow in a timely, reliable, and uniform manner, [25]. Moreover, key *Industry 4.0* features within the construction value chain are vertical and horizontal, with end-to-end integration of the value networks, [11]. Horizontal integration represents the collaboration among organizations to form an ecosystem where information and material can flow efficiently, [26]. The vertical integration can be achieved within organizations through integrating the physical and information management systems while end-to-end integration focuses on value creation along the supply chain activities throughout the entire life cycle of the product which includes customer requirements, design, production, maintenance, and disposal, [26]. *Construction 4.0* promotes the implementation of modern technologies to support the integration and digitalization of the construction supply chain,[24]. Industry 4.0 represents the future and construction should embrace it [27] where technologies on future construction sites will be integrated to improve communication, safety, higher computational powers and efficiencies, [28]. The study aims to use value stream mapping (VSM), which is a lean management tool, to support eliminating wastes and increase efficiencies for construction processes at the field level. Taking into consideration the characteristics of Construction Supply Chain (CSC) (i.e., projects are built as per owner requirements, every project is unique, temporary supply chains involve large numbers of partners in nonrepetitive processes, and the project exists in an uncontrolled environment, [29]), current state VSM can be developed but implementing future state map can be challenging. It has been argued that traditional construction is not ideal for the application of VSM and more studies should focus on implementing VSM for nonrepetitive construction processes, [30]- [31]. Moreover, literature review shows there is a research gap in terms of focusing on the execution of the future state maps for the less repetitive processes at the site level as well as monitoring it. The objective of this study is to develop a VSM framework that suits the less repetitive processes in construction, which are mainly onsite construction ones, as well as focuses on implementing future state map. Ontology approach can support the implementation of the VSM for construction processes by facilitating information flows across enterprises. An intensive literature review for ontology development in the construction industry identified five significant research gaps: the lack of standard methodology for ontology development, absence of an automatic or semiautomatic framework for ontology generation, deficiency in philosophical basis, lack of developed ontologies in construction, and efforts that are focused on specific project types and phases, [32]. The study aims to follow the Basic Formal Ontology (BFO) structure to develop an ontology to structure construction information. Using the BFO structure provides a mature methodology and automatic method to develop an ontology for construction knowledge, with a philosophical foundation. The study aims to develop an upper ontology that covers all the life cycle phases of the construction project, i.e., starting from conceptual design to the disposal phase.

1.2 Background

Construction is a major industry in Canada, with approximately $142 billion spent on construction-related services and goods in 2018, [33]. Regardless of the construction contributed to the economy, its supply chain is the least integrated among all other major sectors, [2]-[3]. Researchers have defined the construction supply chain (CSC) differently. Simchi et. Al defines it as the management of information and money flows to build a construction project while Utomo et. Al defines it as a system where stakeholders work together, share information, supply, and install materials, equipment, and other resources to deliver a construction project to a client, [34]- [35]. The main reasons for the fragmentation of the CSC are the large number of companies and the wide variety of trades involved in a project, [36]-[37] and the industry's continued reliance on assembling teams on a project-by-project basis with contractors often managing the supply chain, [38]. This approach has been proven to be inefficient and often leads to miscommunication, [39].

Construction has a temporary supply chain due to the transient relationship among stakeholders, [40]. The consequences of such a relationship are lack of trust, coordination, and collaboration as well as miscommunication among project partners, [41]. These consequences have resulted in a fragmented supply chain where each partner prefers to work on his own which often leads to poor knowledge flow, inaccurate documents, un-met information needs, incorrect information, wrong deliverables and extended waiting time for documents approval, [38], [42]. This led to major negative performance such as low productivity, high cost, schedule delays, inadequate specifications, and claims, [38]. Such fragmentation in the supply chain imposes challenges for generalization or standardization of the industry's processes.

Construction projects involve companies from a wide variety of trades; a medium-sized project can include hundreds of various companies that supply equipment, materials, and labour to perform the work, [43]. Moreover, the industry relies on a fragmented and largely subcontracted workforce [44], where construction companies only execute a small portion of the project and depend on subcontractors and suppliers to perform the majority of the work to mitigate and spread the risks, [45]. Having a large number of partners can result in poor communication and less collaboration among the partners, [38]. Besides the larger number of partners, the construction supply chain has multiple levels (e.g., the contractor is the subcontractor's client, while the contractor is the project owner's client), therefore, there are often multiple end customers, [46].

Furthermore, the industry is primarily driven by cost, where the cheapest bid typically wins the contract, which has led to a conservative industry that invests less in innovation and adoption of new management principles and tools. This has become a fundamental problem within the construction industry, [47]; such conservative cultures will often resist changes to their structure, [48].

These characteristics and challenges have adversely impacted the construction industry's performance. The industry has been suffering from a high percentage of physical and processes wastes where more than 50% of construction time is considered waste, [49]. Proper planning is crucial for the success of a construction project, [50]. Project planning is a set of directions that tells the project team what to do, when to do it, and the resources that are needed. It aims to reduce uncertainties, improve efficiencies, and establish baselines to monitor and control construction execution, [51].

VSM is a lean management tool that aims to identify and eliminate wastes to improve efficiency and create better value for the customers by visualizing the material and information flow for a process, [52]. On the other side, *value stream management* consists of VSM and *value stream design* (VSD), [53]. VSM is based on observing the process to create the current state VSM and then identify and eliminate the wastes in the future state map, [52]. Therefore, future state VSM can be implemented when the process is repeated. However, construction is a project-based industry where nearly every project is unique, and most activities are nonrepetitive, [29]. Therefore, VSM in the construction industry cannot easily be implemented in a traditional VSM methodology. The study aims to develop a generalized VSM framework that implements VSM during the project's planning, pre-construction activities, to eliminate wastes before the execution phase and enhance information flow to downstream phases. Proper planning is crucial for the success of construction projects; poor planning can result in a project's failure, [50]. Also, the study aims to develop an ontology-based system to structure the CSC knowledge to support the integration of the construction value chain.

1.2.1 Lean Management

The evolution of the production system is closely related to the Toyota Motor Company, [54]. In the early 1950s, the Japanese automotive industry was underperforming compared to the American industry because the Japanese market was relatively small with limited labour, natural, and financial resources, [55]. Toyota realized its production cannot compete with American carmakers, and they need to "catch up within three years; otherwise, the automobile industry in Japan will not survive", [56]. This necessity to survive led to the born of lean principles. Toyota started to restructure its assembly lines, integrate suppliers with its supply chain, and engage the workforce to optimize production, [55]. Toyota goals were to reduce cost, improve quality and minimize production lead time; and to achieve these goals, *Toyota Production System* (TPS) was built on two pillars: (1) *just-in-time* (JIT) and (2) *judoka* which is the Japanese word for automation, [57]. JIT concept is based on ordering needed materials, in the right amount, and at the right time to minimize inventory and achieve continuous workflow, using a pull system while Judoka is the automation of processes to eliminate defects and separate human and machine works, [57]. These pillars built on the foundations of continuous improvement, standardizing, and leveling work concepts, [57]. Implementing these principles, known later as lean principles, shaped a culture of continuous improvement that turned Toyota from a company struggling to survive to an organization that led the industry, outperforming other carmakers in the 1990s, [55]. TPS and lean principles can be summarized as, [58]:

(1) Maximizing customer values

(2) Management of value stream

(3) Developing continuous flow in the production system

(4) Implement pull planning system

(5) Elimination of wastes

The manufacturing Lean principles became management principles across all industries, [59]. Construction implemented lean principles as well as developed systems based on the lean concepts that are specific to the industry such as the *last planner system* (LPS), [60]. Implementing Lean in construction has been facing many challenges because of the fragmentation of its supply chain, largely subcontracted work, financial issues, inadequate performance measurement systems, lack of top management commitment, and poor education on lean principles, [61].

1.2.2 Process Mapping

TPS is a process-driven system that aims to standardize work through continuous improvement and increase efficiencies to maximize the product's value to the customers, [57]. Process mapping such as VSM is one of the fundamental tools that can be used to identify and eliminate wastes which ultimately supports achieving TPS goals, [57]. Harrington [62] defined the process as a set of activities that takes inputs, adds value and transform it to an output while Davenport [63] defined it as a sequence of activities that take place during a period, in a place, has a start, an end, inputs and outputs. A process can be demonstrated with two approaches: *bottom-up* and *top-down*. The bottom-up approach focuses on the individual activities and grouping them based on their interactions to form a process while the top-bottom which is the most common approach focuses on the whole process from the input, output, and added value perspectives, [64]. Process mapping is a technique used to understand an existing process and redesign it to improve its performance and ensure customer satisfaction, [65]. It is an intervention and analytical tool that visually shows the relationships among activities and initiates discussions among process stakeholders to understand their relationships, [65]. Process mapping can simplify the workflow, identify and eliminate wastes, increase resource utilization, improve quality, and enhance communication and cooperation, [66]. It is a visual tool that aims to improve existing processes and different from process reengineering that involves fundamental changes to a process. Process mapping can support the reengineering of a process, [66]. There are many process mapping techniques, [66]:

- *block diagram* shows a process sequence,
- *flow chart* identifies process flow and paths as well as decision steps,
- *quality process language diagram* shows information interaction with a process,
- *operations chart* identifies value-added and non-value-added steps,

- *string diagram* shows the physical flow of activities,
- *value stream mapping* is a lean tool that shows information and material flows.

1.2.3 Value Stream Mapping

Value-stream mapping (VSM) came to prominence in the latter half of the 20th century and became one of the foundations of the Toyota Production System, [67]. It is a graphic representation of chain value flow from receiving customer order to the delivery of the final product or service. It divides activities into value-adding and non-value adding activities and helps to visualize the whole production process by showing information and materials flows as well as the sequence of activities. It also documents the relationships between process and production controls such as scheduling and information management systems, [57], [68].

The traditional VSM methodology can be summarized in the following four steps, [3], [68], [69]-[70] :

(1) Collection of process data
(2) Develop current VSM
(3) Analyze current VSM
(4) Develop and implement future VSM

(1) Data Collection

Data related to processes such as activities, sequences, resources, the relationships among activities is collected to understand the current process starting from receiving customer order to the delivery of the final product. The customer needs are identified to facilitate value creation. Process activities and their relationships which include information and material flows are determined, [68].

Data can be collected by using tools such as field walks, discussions with people involved in the process, as well as using documents and information management systems. The purpose of this step is to analyze and understand the process that needs to be mapped, [68]- [69].

(2) Develop Current State VSM

In this step, the current process is mapped to develop the current state VSM which is a mirror image for how the current process. Current VSM shows the process metrics such as process time, lead time, crew size, information technology, quantities, and queue that measure the process, [52], [68]. Material and information flows should be shown as well as the sequence of activities. The level of detail should be determined by the mapping team and in accordance with the purpose of implementing VSM. The current VSM should be socialized with process stakeholders to ensure its accuracy. It can be drawn on a board, or on paper, or using software, [68],[69].

(3) Analyze Current State VSM

The current VSM should be analyzed to identify value and *non-value-added activities* (NVA). NVA can be classified into two categories; (1) essential NVA which cannot be eliminated due to constraints such as capacity or technology and (2) wastes that should be eliminated, [71]. There are seven types of wastes as defined in the TPS, [56]:

(a) **Waste of overproduction**: Producing more than needed which includes requesting quantities more than the customers need or earlier than needed that Toyota calls "created demand". It is one of the major issues in supply chains, [72].

(b) **Waste of time on hand (Waiting)**: any delays between processes which also include workers or machines waiting to start work or partially finished work waiting for processing.

(c) **Waste of Transportation** (Transportation): unnecessary transport that results in added costs e.g. extra handling of materials.

(d) **Waste of processing itself**: extra processing steps that are not needed by the customer

(e) **Waste of stock on hand (Inventory)**: extra materials or products in hand that are not needed e.g. producing more than needed and storing them.

(f) **Waste of movement (Motion)**: unnecessary moving of materials/people or products that adds extra costs.

(g) **Waste of making defective products (Defects)**: producing faulty items that don't meet customers requirements and must be fixed or recycled.

(4) Develop and Implement Future State VSM

After eliminating wastes, the future state VSM can be developed. It shows the improved process that should be implemented. The improvements may be implemented in several stages which depends on the purpose of implementing VSM as well as the constraints such as available resources to implement these changes.

1.2.4 Lean Management Tools

In analyzing the current state VSM and developing future one, many lean management tools such as *kanban*, *JIT, pull system*, *plan-do-check-act* (PDCA) can be implemented, [57]. Such tools can facilitate identifying and eliminating wastes as well as achieve continuous flow in the process with minimum interruptions. Following is a summary of major lean management tools:

- **Just-in-Time (JIT)**

  TPS addressed the supply issue through just in time which is the supermarket model where people buy only what they need when they need it, in the amount needed. On the other side, door to door sellers may carry products that may not sell which is a waste of time and resources, [57]. In the manufacturing process, the latter process gets only what it needs from the earlier process, then the earlier process produces what's taken. JIT reduces the inventory which eliminates the costs needed to handle, store and pay for the extra inventory, [57].

- **Kanban**

  Kanban is a system used to control inventory levels and components' supply. Kanban prevents overproduction because it starts downstream in the final process and works backward to determine what's needed, so it controls the flow of goods in the production line, [56]. The most common form of Kanban is a paper-based instruction for the worker that includes pick up, transportation, and production information, [73].

- **Pull System**

  Pull system produces as per customers' needs i.e. the downstream processes and customers pull their needs from the producers. The upstream processes only produce what the downstream ones need and at the time needed, [74]. On the other hand, the push system produces based on a set schedule and pushes the products and components to the downstream processes and customers whether they need them or not, [57]. Pull system is based on flowing products in small batches and one-piece flow if possible, to reduce Work in Process (WIP) as well as inventory. WIP is partially completed products in the production system. Takt time also is used to control the pace of flow to minimize overproduction and the Kanban system can be implemented to signal the replenishment and level out the work. Pull systems can enhance the workflow, minimize the inventory, and reduce WIP which can eliminate wastes, [74].

- **Level out the Workload**

  The TPS aims not only to eliminate the waste (Muda) but also to reduce the overburden (Muri) of people and equipment as well as the unevenness (Mura). Overburdening the system may cause safety and quality issues. Therefore, the production units and workstations should be loaded with the right amount of work to avoid workers fatigue, equipment breakdown, and defects, [57]. The aim of eliminating unevenness is to minimize the variations within the process i.e., peaks and valleys. In a normal production process, at some time the system can have more work than its capacity and other times will have a lack of work, [74]. This will increase the inefficiency when the system is underutilized and impact the quality when it is overloaded. Therefore, eliminating the wastes, levelling the workload, and minimizing the overburden can achieve a stable workflow that can deliver products efficiently, [57].

- **Kaizen: Continuous Improvement**

  Toyota promoted a self-learning culture to continuously improve its operation by implementing tools and techniques to find the root causes for the problems, provide countermeasures and ensure knowledge is transferred to the right people to prevent the repetition of the same mistakes. It also empowered its employees to promote the continuous improvement culture, [56].

Toyota is a process-driven company that invests long term in its people, tools, and processes. The goal is to create value for the customers by continuously increasing efficiencies and eliminating wastes, [57]. Kaizen is implemented in stable and standardized processes to improve them. 5-whys is another technique used to find the root causes of the problems by asking the why question five times. Every time why is asked it unpeels a layer till the real root cause is determined, [57].

PDCA cycle is another kaizen tool used by Toyota, and it is very effective in unwrapping the root causes of the problem and implement solutions, [75]. In the "plan" phase, the data is collected, and the problem's root cause(s) are determined. The improvements and solutions are implemented and measured in the "Do" phase; then the results are analyzed and evaluated in the "Check" phase. If the solutions are deemed acceptable, the process will be standardized in the "Act" phase if not the cycle will be repeated, [75].

- **Jidoka: Stopping the Process to Fix Problems**

  Jidoka is the second pillar for the TPS and based on detecting defects in the production line when they occur and fix them before they move downstream, [57]. It minimizes the defective products and promote a culture of building things right at the first time. Andon is one of the tools Toyota used to implement Jidoka. Andon is a signalling system that uses lights placed by machines and when an error occurs the worker turns the light on, asking for help, [48]. Jidoka built high-quality TPS which became one of the major features for Toyota products, [76].

- **Standardization**

  Standardization prevents the recurrence of defects and mistakes and became an important aspect of the TPS. Standardization in TPS has three major elements: (1) takt time, which is the time required to complete one job at the pace of customer demands, (2) the sequence of activities, and (3) the level of inventory needed to complete the work. Toyota aims to make shop floor tasks repeatable and efficient. Moreover, Toyota standardized the office work as well such as engineering through guidelines and standards, [57].

The crucial task in standardization is the ability of the standards to provide guidelines for the workers to perform the work and be flexible to allow innovation. Rigid standardization can hinder innovation and personal growth. TPS implemented a flexible standardization that promoted innovation and personal growth, [57].

1.2.5 Value Stream Mapping in Construction

The term value stream was introduced in 1990 by James Womack, Daniel Jones and Daniel Ross in the book, *The Machine that Changed the World*, [77], and further developed by Jame Wack and Daniel Jones in *Lean Thinking* in 1996, [78]. In 1999, Mike Rother and John Shook transformed the understanding of the work flow and VSM in their seminal book, *Learning to See*, [52]. Then, VSM has been widely applied in many sectors and emerged as a lean fundamental tool by its ability to establish a direction to design the work process by deepening the understanding of the process from the customer's perspective, [79]. It's ease of use and ability to reduce wastes made it very attractive, [79]. It has been implemented in the healthcare sector to improve the operations of emergency rooms and departments in a hospital. The results show VSM can be an effective tool to improve operations in healthcare, [80]. Villaleneal et. Al [81] applied VSM to improve the efficiency of the transportation supply chain by focusing on physical distribution. It was also implemented in Software Product Line Engineering as well as a product development process for a US-based mining SME, [82]-[83]. Moreover, VSM has been utilized by experts in the food industry to reduce food losses and wastes and to promote innovation management, [84].

The lean philosophy has been introduced to the construction industry since early 1990s, [85]. The *Transformation Flow Value* (TFV) theory discussed the construction projects in terms of production system i.e. trasforming inputs to ouputs with flow and value concepts which supported the classification of value added and non value added activities in project mangament. TFV theory became a corner stone for lean construction, [86]-[87]. As VSM evolved during the late 1990s, the construction industry adopted it in early 2000s. In 2003, few studies implemented VSM to the construction supplies but not to production processes, [85]. In 2005, Pasqualini et. al discussed the modifications of VSM, so it can be implemented in construction, by mainly focusing on productive activities, customers, suppliers and the value flow of the process. The study selected the masonary pavement stage to implement VSM. The construction project occurs over a relatively long period of time and different processes produce different products, so VSM in construction should be applied to a selected stage, [85]. Later, many studies have implemented VSM in onsite construction processes such as installing cast-in-place concrete [69], [88], structural steel erection [89], drain construction project [90], and structural masonry case studies, [91]. The focus of these studies was to develop the current and future state maps but not the implementation of future state maps that in most cases cannot be applied as these processes are less repetitive. VSM is worthless if a future state map is not executed, [52].

Several studies have implemented VSM in construction processes that use manufacturing production systems. In 2008, Fontanini et al. implemented VSM to improve the production of precast concrete elements, [92]. More studies later focused on precast buildings and elements [3]-[93]-[94], prefabricated steel frames [95]-[96], and modular construction [97]-[98]-[99].

Few studies later focused on implementing VSM in the administration tasks of the construction companies. In 2009, kemmer et al. implemented VSM in payments' process [100], and Garret et al. used VSM to improve submittals' review process in 2010, without extending it to the site activities, [101].

In 2009, Yu et al. implemented VSM to the housing construction. Taking into consideration construction processes are less repetitive compared to manufacturing, the study collected data for 400 houses and viewed it as repetitive work. The sequence of activities, materials and using same subcontractors can be repetitive for all housing, but many factors may impact the application of VSM such as mapping level and variations in site conditions, [30]. Moroever, the model may not be applied for construction projects that cannot be replicated.

There have been many attempts to use VSM to support sustainable and green construction projects. In 2011, Vieira et al. studied the relationships between lean construction tools and techniques including VSM, and *Sustainability Construction Index* (SCI) in a Portuguese construction company, [102]. Rosenbaum et. al discussed implementing VSM to improve environmental production in a construction project, [69]. Then more recent studies used VSM to support green construction through waste elimination, [103]-[104].

VSM has been used to improve the design of construction projects. In 2013, Leite et al. implemented VSM to the design phase of the housing project, [105], and other studies focused on standardizing the information flow for an architectural firm [106], as well as support the elimination of wastes in structural design process, [107]. However, these studies did not extend the VSM to the onsite construction processes.

Recent studies used VSM to improve non-production processes. In 2019, Cavdur et al. study combined VSM and simulation-based methods in a university maintenance and operation case study, [108]. In 2020, Wang et al. integrated VSM with work posture analysis to improve construction safety using a scaffolding case study, [109], and VSM has been implemented to improve operation training by using a case study of erecting scaffold, [110].

Rother et al. introduced the concept of multilevel VSM mapping (process, plant, multiple plants, and across companies), [52]. In 2016, Oberhausen et. al. discussed the multilevel VSM concept in the manufacturing industry, in an attempt to standardize it, as following:

- Macro level: different companies
- Meso level: subnetwork- supply chain for transport
- Micro level: within the company
- Nano level: single process

The validation of the multilevel VSM, as shown in Figure 1, concept can be a key to standardize VSM which facilitates collaboration and communication within supply chain networks, [111]. In construction, VSM found in literature is mainly focused on the nano or micro levels; however, the challenges will be completing VSM at meso or macro levels where multiple partners are involved. Therefore, efficient information management systems across enterprises can be a key to multilevel VSM in construction supply networks.

The benefits of VSM have been illustrated in many sectors and its implementation is still growing in all domains including manufacturing, [79]. However, VSM is still inadequately applied in many cases such as developing only the current VSM and ignoring future one which could be due to the weakness of the traditional VSM that may not be suitable for all sectors as well as lack of its standardization which leaves it to the users' judgments to figure out the most suitable methodology for applying it, [79].

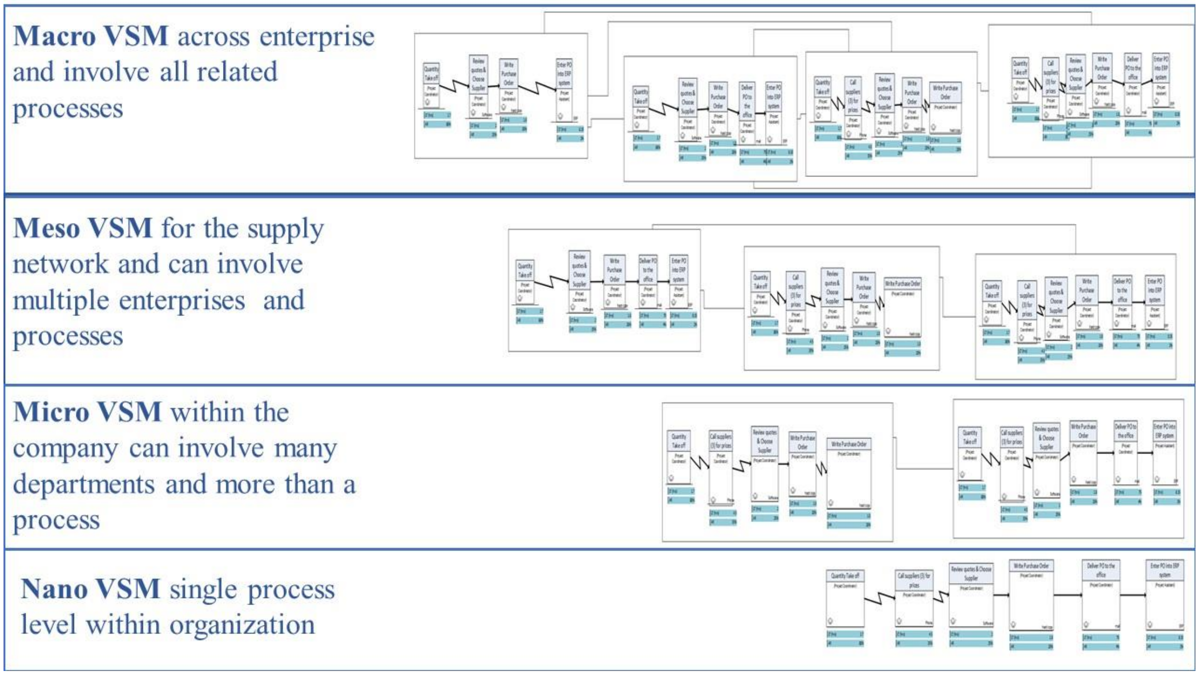

Figure 1: Multilevel VSM (adapted from [111])

VSM is an effective tool in replicated processes by identifying wastes and inefficiencies in the current state map and implementing the improvements in the future state map. However, taking into consideration the characteristics of CSC i.e. projects are built as per owner requirements, every project is a unique, temporary supply chain that involves a large number of partners in nonrepetitive processes and uncontrolled environment, [29]. It can a challenge to implement current VSM methodology in traditional construction processes that are less repetitive. Current state VSM is developed by observing the existing process and then develop a future state map that reflects the improvements. It is a challenge to implement the future state map in a less repetitive process. Construction processes at the field level are less repetitive because every construction project is unique in terms of design, location, stakeholders, and site conditions that are subject to change due to weather, location, and logistics, [29]. VSM is worthless if a future state map is not executed, [52]. Studies in literature mostly focused on developing the current state map and less effort dedicated to execution of the future state map. The industry needs to work on implementing VSM in non-repetitive processes and non-typical activities, [30]-[31]. The study examines the extent of adoption of VSM in Alberta's construction industry and proposes a framework to implement VSM during the planning phase of the project and utilize it as a monitoring and controlling tool at the field level for the less repetitive processes.

Planning is a crucial practice and a key to the success of a construction project. Project planning is defined as a set of instructions given to the project team to tell them what to do, when to do them and the resources needed to complete the work. The major outcome of the project planning is a plan that contains the project's overview, activities needed to reach the project's objectives, schedule, resources and evaluation criteria to measure progress and success, [112]. Proper project planning can minimize project uncertainty reduce risks, develop a good understanding of the project's objectives, and establish a basis to monitor and control performance during the construction execution phase, [51]. Therefore, implementing VSM in project planning can support the success of the project.

VSM is a graphical representation of material and information flows, and multiple partners such as engineers, general contractors, material suppliers, project owners, architects, and subcontractors can be involved in a construction process, [38]. Therefore, information flows across enterprises in construction processes. Moreover, data related to processes and activities may require to be collected from multiple partners to develop the current and future state VSMs. Therefore, data structuring and efficient information flow can be keys for VSM across enterprises. The industry has been lacking the development of a standardized ontology that can structure its data as well as provide an interoperable knowledge modelling framework, [32].

1.2.6 Ontology Literature Review

Ontology is a representation of domain knowledge in the form of concepts, their relationships and properties, [113]. It provides a framework to manage and share domain knowledge in an interoperable manner. Due to their abilities to explicitly define domain knowledge in a machine-readable form, ontologies have been used in many domains such as Web development (e.g. Yahoo.com categories), shopping catalogues (e.g. Amazon.com), and data integration (e.g. Resource Description Framework), [114]. Ontologies have also been utilized in artificial intelligence to support knowledge sharing and reuse, [115]. Ontology can have many benefits to the construction domain such as integrating information without loss or misunderstanding, facilitate communication among various software systems and promote building automation, [32]. These are key features for enabling *Construction 4.0*.

Taking into consideration the aim of designing an ontology, ontologies can have three different meanings. The first meaning is philosophical, in which the ontology studies the kinds and structures of objects, properties, events, and relationships to produce a description of what exists as representational artifacts, [116]. The second meaning is the domain ontology, which represents entities and their relationships in a domain or area of study, such as biology or law, [113]. The third meaning is a formal or top ontology that supports communication among domain ontologies, such as the *standard upper merged ontology* (SUMO), [117]-[118]. Ontologies have been applied to a wide range of sectors to facilitate communication, integration of databases and retrieval of information, etc., [119].

Ontologies can be classified into two main categories: application ontologies that are designed to achieve specific tasks and reference ontologies that are developed to encapsulate established knowledge in specific domains, [120]. In construction, various domain and application ontologies have been developed to satisfy particular needs and purposes, such as information retrieval and organizing construction knowledge, [121]-[122]. Ridder et al. [119] conducted a study to develop an ontology that focuses on the classification of documents generated in construction projects, while El Dirby [123] focused on developing a domain ontology to generate one of many representations for construction knowledge. Dhaka et al. work focused on developing an ontology-based system to support the reasoning and representation of knowledge for the disaster-resilient practices at construction sites, [124]. Other studies focused on developing ontologies related to construction safety, such as developing an ontology to identify safety risks in metro construction [125], and identifying hazards by integrating computer vision and ontologies, [126]. Ontology-based systems can support information management in construction [127] by integrating data from various construction applications, such as *Building Information Modelling* (BIM) and *Geographical Information Systems* (GIS), due to their high effectiveness, extensibility, and medium-cost compared to other approaches, [128]. Technologies such as GIS facilitate organizing and communicating information related to construction facilities, [129]. Ontologies have been developed in the industry to support specific needs without extending them towards a complete domain ontology [130], such as ISO 15926 which is a standard for managing the data for process plants including oil and gas facilities, [131]. Construction still lacks domain ontologies to support specific requirements, such as the need to develop an ontology-based system for modelling construction workspace requirements, [132]. Developed ontologies in the construction industry has mainly focused on specific use within enterprises, without covering the entire project phases mostly. Ontologies in construction are still in the early stages of development and far away from maturity, [32].

An intensive literature review for ontology development in the construction industry identified five significant research gaps: (1) the lack of standard methodology for ontology development, (2) absence of automatic or semiautomatic framework for ontology generation, (3) deficiency in philosophical basis, (4) lack of developed ontologies in construction, and (5) efforts are focused on specific project types and phases [32]. The industry lacks standard and complete ontologies which impacts the information management across enterprises. Taking into consideration these research gaps, this study aims to develop an ontology that represents the construction knowledge following the *basic formal ontology* (BFO) structure which is a mature ontology that has been widely applied in many domains such as natural sciences and information technology. BFO has been widely used as an upper ontology by hundreds of ontologies, [133]. BFO is based on fundamental distinct between continuants and occurrences. Continuants represent continuous existence in time such as objects and occurrences represent processes, events and changes, [113]. Continuants have three subclasses: (1) generically dependent continuant, (2) independent continuant that has material and immaterial entities as subclasses and (3) specifically dependent continuant that has quality and realizable entities as subclasses. On the other side, occurrent has four subclasses: (1) process, (2) process boundary, (3) spatiotemporal region, and (4) temporal region. The summary of the BFO structure is shown in Figure 2.

It is very difficult to develop an ontology that can cover all the concepts within a domain and satisfies all the needs, [134]. It is also expected that many different ontologies can be developed to describe the same knowledge, [123]. Therefore, in designing and developing ontologies, the purpose of the ontology should be defined clearly as well as its interoperability with existing ontologies should be taken into consideration. The study aims to use the BFO structure to develop an upper ontology that covers all the life cycle phases of the construction project, i.e. starting from conceptual design to the disposal phase. The ontology can be used as a framework to manage and structure construction knowledge. Using the BFO as an upper ontology provides a mature methodology and automatic method to develop an ontology for construction knowledge, with a philosophical foundation. It was estimated that 50 person-years are required to develop a complete ontology for construction knowledge, [122]. Therefore, the purpose of this study is not to develop a complete ontology, but an upper ontology that can be used by construction companies and experts to structure their knowledge and further detail it towards a complete construction ontology. This supports the integration of the construction supply chain by structuring its data, which facilitates knowledge management and the implementation of Construction 4.0. Many Industry 4.0 applications, such as robotic agents, require a structured representation of concepts to develop interoperable communication models, and ontology-based systems can be a solution in this domain, [135]. Ontologies can be used to develop a mechanism that facilitates the exchange of

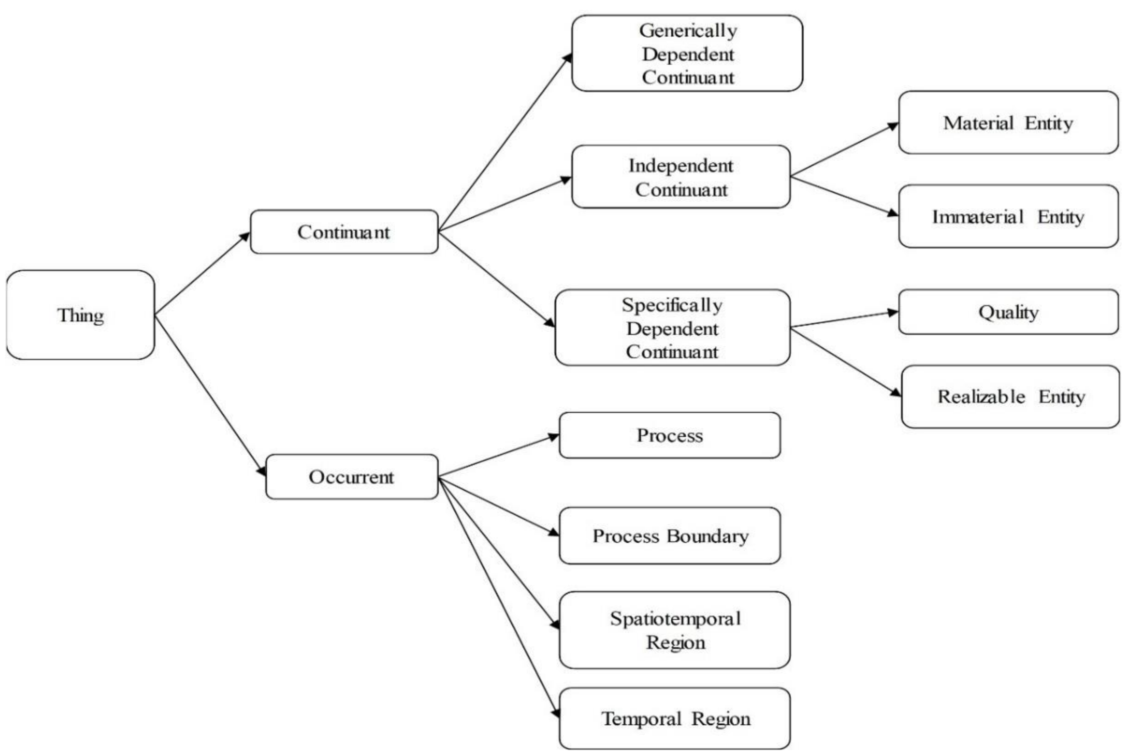

Figure 2: BFO Structure

knowledge in the construction sector as well as communicating it with other domains, For example, communicating information related to energy consumption and Green House Gas (GHG) emissions for buildings with stakeholders can urge them to take actions to reduce these emissions [136]. A complete ontology that covers the entire project life cycle will structure such information which facilitates collecting and communicating it with stakeholders. The study aims to follow the BFO framework to build a construction ontology.

1.3 Research Questions

The study is seeking to answer the following four research questions:

(1) What is the current state of information flow tools and the extent of adopting VSM in Alberta's construction industry?

(2) How VSM can be implemented at multilevel to identify current wastes in the industry?

(3) What are the requirements for a VSM framework that is suited for less repetitive construction processes at the field level?

(4) How the construction industry can structure its information to facilitate its management as well as applying VSM across enterprises?

1.4 Research objective

The study aims to develop a VSM and information management frameworks to support the integration of the construction supply chain and enhance the performance of its non-repetitive processes at the field level. The frameworks can be suited to accommodate fluctuation, capture process disturbances and enhance construction processes' efficiencies which can promote the implementation of *Construction 4.0*.

Traditional VSM methodology requires observing the current processes to map it and implement improvement in future state map. However, construction projects are unique and onsite processes are most likely nonrepetitive. Therefore, implementing a future state map can be a challenge as the future process most likely will not occur under the same conditions. Current VSM is effective in manufacturing where processes are repetitive. VSM for construction processes found in literature has been completed at the nano or micro levels i.e. within enterprise boundaries. However, many construction processes involve multiple partners where VSM at Meso and Macro levels should be completed. To develop VSMs at multiple levels, information and knowledge modelling for construction is required to structure its data in an interoperable manner. The industry has been lacking a standardized methodology for the development of a domain ontology that has a philosophical foundation and covers all project phases. The study aims to develop a Value Stream Mapping and information management frameworks to support the integration of the construction supply chain and enhance its performance at the field level. The frameworks can be suited to accommodate fluctuation, capture process disturbances and enhance construction processes' efficiencies which can promote the implementation of *Construction 4.0*.

Ontology-based systems are a promising approach in knowledge management by defining domain concepts, their properties and relationships, [137]. The construction industry still lacks a consistent methodology to develop a domain ontology. The study aims to develop an upper domain ontology by using the BFO structure, incorporating ISO 12006-2 recommendations, [138] and conducting interviews with domain experts. BFO is a mature upper ontology [139] that has been used in developing hundreds of ontologies in various domains, [133]. Therefore, developing construction ontology using the BFO structure can support its interoperability with other domain ontologies and establish a philosophical foundation for it. The thesis has four objectives:

(1) Determine and analyze existing information flow tools and the extent of adopting VSM in Alberta's construction industry.

(2) Apply VSM to determine the current wastes induced in the construction processes and understand the requirements for applying VSM across enterprises.

(3) Develop and validate a VSM framework for the less repetitive onsite construction processes.

(4) Structure construction information using ontology approach to support the application of VSM across enterprises.

Taking into consideration the culture of the construction industry that has been resisting changes for a long time, the industry needs to focus on the social, cultural and technological aspects of the changes in moving towards enabling the concepts and technologies of Construction 4.0, [49]. The aim of implementing VSM at the field level is to eliminate wastes and enhance efficiencies for these processes that are still mainly dependent on labour forces. More efficient or automated processes can be understood as fewer workers will be needed to execute the work. This may spread the fear of losing jobs among workers, so it should be communicated that the aim of implementing such processes and tools is to move the resources to work in other areas, and there should be no fear regarding job security. Reducing wastes and increasing efficiencies allow us, as a society, to better utilize our resources. Moreover, building a complete ontology for the construction industry may introduce security issues regarding integrating data and sharing information, so this should be addressed and resolved to manage the risks associated with its implementation.

1.5 Thesis Overview

The dissertation consists of seven chapters. The first (1) chapter states the motivation for the study, objectives, and related work through a literature review. The second (2) chapter discusses the research framework that is adapted to achieve research objectives. The third (3) chapter addresses the first research objective which is determining the existing information flow tools and techniques currently used in the industry by conducting surveys and interviews with industry experts. The fourth (4) chapter summarizes case studies that implement VSM in the construction supply chain to understand the current state of the industry, opportunities for improvements and limitations of current VSM methodology which fulfils the dissertation's second objective. Chapter five (5) discusses the developed VSM framework for construction processes, the implementation and validation of the framework to fulfil desertion's third objective. In chapter six (6), construction knowledge ontology is developed and evaluated to fulfil the dissertation's fourth objective. Chapter seven (7) states the study's conclusion, limitations, and recommendations for future work. The summary of the dissertation's roadmap is shown in Figure 3. The background is discussed in chapter one. Literature review is discussed in chapter two. The four objectives as shown in Figure 3 are addressed in chapters three, four, five and six respectively. The conclusion and future work are stated in chapter 7.

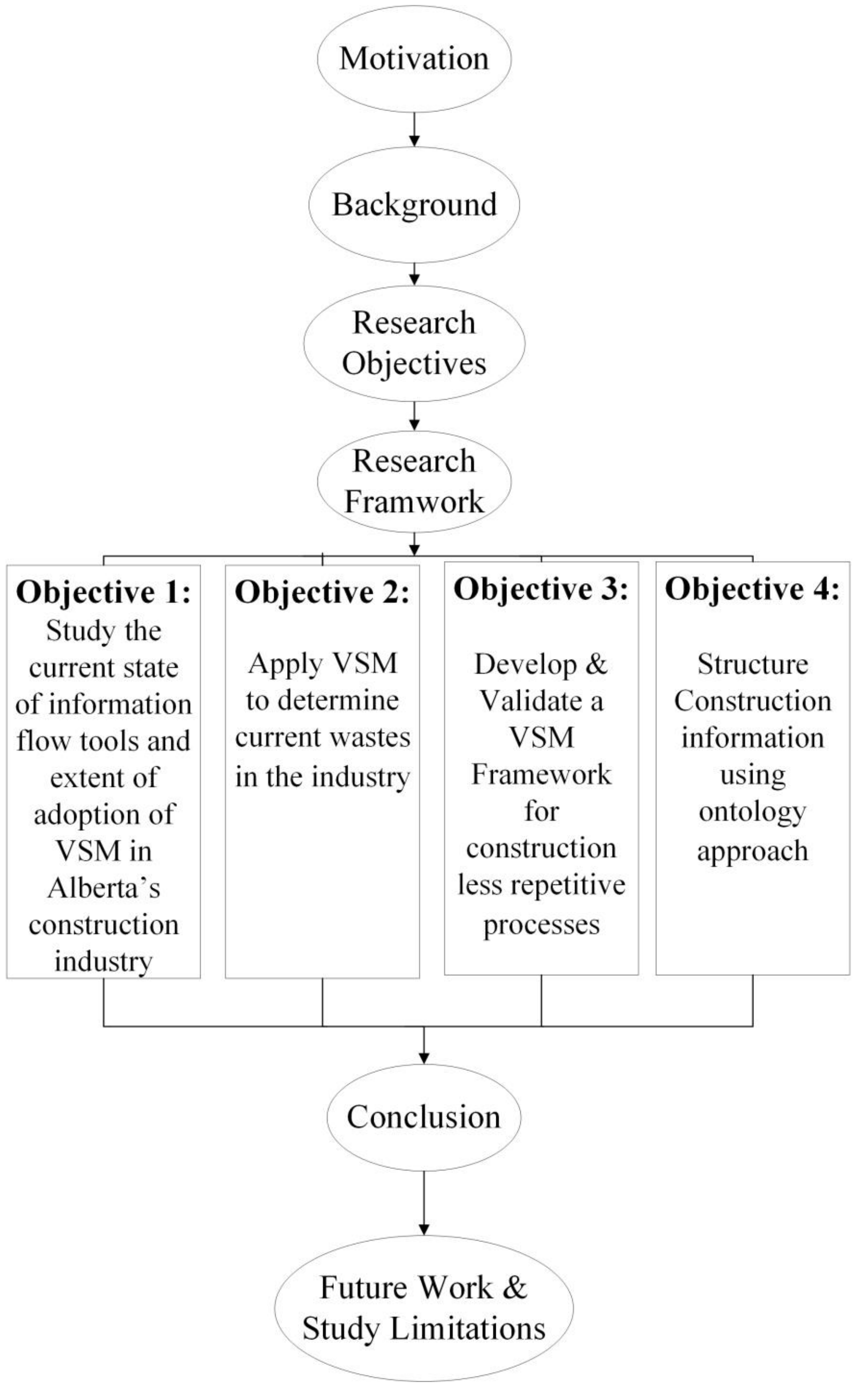

Figure 3: Thesis Roadmap

Chapter 2: The Research Framework

The research framework defines the research process i.e. how is the research designed and executed? How the theories are developed and tested? On the other hand, the research method refers to the specific techniques and tools used to collect and analyze data, [140]. The three main research methods generally used are quantitative, qualitative and mixed, [140].

2.1 Qualitative Method

Qualitative methods are used to answer questions that cannot be investigated by quantification such as behaviour, [141]. In the qualitative paradigm, the researchers are seeking to capture experiences and knowledge of the participants that are involved in a phenomenon by using techniques such as interviews, observations, and case studies, [141]-[142]. Qualitative analysis focuses on the process and meanings that are not measured in the form of quantity, frequency or magnitude, [143]. It has many benefits such as providing a deep understanding of a topic by closely studying it, supporting the understanding of complex phenomena, explaining an existing knowledge obtained from the quantitative study, and helping study a phenomenon that cannot be approached quantitively, [144]. Interviews are one of the most common tools used in qualitative research methods.

2.1.1 Interview as a research method

Interviews are a systemic method to collect data and gain knowledge from individuals through conversations. Interviews can be used as a research tool when highly personalized data is required, researching a topic with little or no knowledge exist about it or the knowledge still at the tacit level, and obtaining experts opinion on the topic, [145]. There are several types of interviews, [146]:

- **Structured Interview**

A structured interview is also called standardized interviews. In this type of interview, the same questions are asked to all participants, using the same wording and sequence, [147]-[148]. Questions are usually specific, and the answers have a fixed range which gives the researcher control over the interview. It provides a common format for the data which facilitates its analysis, [149]. However, this type of interview can be rigid and hinder probing a problem. Moreover, the interviewees may understand the questions differently as rephrasing and explanations are limited which can lead to inaccurate answers, [146].

- **Semi-structured Interview**

Semi-structured interviews are non-standardized and often used in qualitative analysis. The interviewer has a set of topics and questions to be discussed during the interview, [150]. The questions sequence can be changed, and extra ones can be asked as needed. The semi-structured interviews provide flexibility where researchers can probe deeper into the topic. Moreover, the researchers can rephrase and explain the questions to ensure the interviewee understands them which provides more accurate answers, [148]. This type of interview requires experienced interviewers who can ask the right questions and probe into the conversation to collect the required data; otherwise, relevant information can be missed. Moreover, it is harder to analyze the data of semi-structured interviews compared to structured ones, [146].

- **Unstructured Interviews**

This is a flexible type of interview that allows the interviewees to speak freely and give as many details as possible to express their opinions and knowledge as well as share their experiences, [146]. Unstructured interviews are suited when no or little knowledge exists about the studied topic. However, this is an inappropriate type for inexperienced interviewers as they may not ask the right questions, and they can be biased. Also, the interviewees have the freedom to deviate from the topic which can lead to irrelevant data. Also, the collected data can have a wide range and in different formats which can create a challenge in analyzing it, [146].

- **Non-directive Interviews**

  Nondirective interviews have no predetermined topic or questions and the interviewee leads the conversation, [148]. The interviewer has the research objective in mind, mainly listening, check and rephrase the answers to ensure accuracy and understanding the interviewee, [148]. This type of interview can support finding deep-rooted problems and feelings such as psychology topics. However, analyzing the data is a challenge as no specific topic or issue to explore, [147].

2.2 Quantitative Research Method

Quantitative research is objective and based on testing hypotheses and theories composed of variables that can be measured and analyzed, [140]. Quantitative methods are used in methodical, experimental and controlled approaches to investigate natural phenomena, [151]. Some of the commonly used quantitative tools are experiments, surveys and symbolic models, [152]. It has been argued that quantitative methods are inflexible and can be limited in testing existing phenomena, [151]. A survey is one of the most common quantitative tools.

2.2.1 Survey as a Research tool

Survey is a research tool used to collect data "to answer questions that have been raised, to solve problems that have been posted or observed, to assess needs and set goals, to determine whether or not specific objectives have been met, to establish baselines against which future comparisons can be made, to analyze trends across time, and generally, to describe what exists, in what amount, and in what context", [153]. Survey has three main characteristics: (1) a quantitative method used to describe a population, (2) the data is subjective as it is collected from people, and (3) the researchers seek to generalize the findings of a data collected from a sample of the population, [154]. Surveys can be conducted in a written format such as paper questionaries' and electronic mail or verbal such as interviews, [155]. There are three types of surveys, [156]- [157]:

(1) **Cross-sectional Survey** collects data at one point in time i.e. a snapshot of what is happening in a population at a specific time

(2) **Longitudinal Survey** collects data over a period which can be months or years. It allows the researchers to compare data for the studied period. Longitudinal survey has two forms:

(a) **Cohort Survey** collects data from the same population over a period of time.

(b) **Trend Survey** collects data from various groups of people over a period of time, using the same questions.

(3) **Explanatory or Correlation Survey** aims to correlate two or more variables using the collected data.

The survey is an efficient tool in obtaining data from a large sample of the population and able to describe it, and the results can be generalized when the sample can represent the population, [157]. Moreover, surveys can identify attitudes which can be a challenge to measure using other tools, [157]. On the other hand, the survey has weaknesses where results can be biased because of inaccurate or lack of responses, and obtaining a representative sample is one of the fundamental issues of surveys, [157].

Table 1 shows a comparison between quantitative and qualitative methods.

Table 1: Qualitative Vs Quantitative Research [140], [158]

Qualitative Research	**Quantitative Research**
Involves Theory building	Involves Testing a theory
Subjective approach	Objective approach
Open Flexible approach	Closed and planned approach
Researchers are close to participants	Researchers are distant from participants
Relatively smaller samples	Relatively larger samples
Low level of measurement	High level of measurement
Reports rich description and narrative	Reports statistical and measurement analysis

2.3 Mixed Research Method

The mixed research method combines qualitative and quantitative approaches. Creswell argued that using the mixed approach can strengthen the research method by counteract the weakness of each approach. It can also give more comprehensive results that neither one approach can do, [140]. A case study is a common mixed research technique. Case refers to an individual, event, entity or unit of analysis. A case study as a research method investigates a phenomenon with its real-life context to explain how and why things happen in a certain manner, [159]. It can provide a holistic view of the phenomena by capturing its full properties which can allow generalization using replicated results of multiple case studies, [160]. The case study approach allows the use of mixed research methods, i.e. quantitative and qualitative analysis, because of its ability to use various methods to collect data in a single study. Moreover, case studies support the study of complex situations that cannot be examined by experiments or surveys, [160].

Case studies have weaknesses in terms of generalization of results when a specific situation is studied, and results cannot be replicated. The case study's results can be biased by the researcher's ability to influence the direction of the findings, [159].

2.4 The Proposed Research Framework

A mixed research approach is implemented to achieve research objectives as shown in Figure 4. Cross-sectional surveys and interviews are conductive to achieve the first objective which is determining and analyzing current tools and methods for information flow in the construction industry. A survey is an efficient research method to describe what exists, in what amount, and in what context, and an interview can collect the tacit knowledge, [153]. To achieve the second objective i.e. current wastes in construction processes and implementing traditional VSM methodology, case studies are completed; case study can answer the questions regarding how and why things happen in a certain manner, [159]. The fourth objective which is developing and validating the VSM framework is completed through case studies and using Microsoft Visio software to develop VSMs. The ontology was developed by interviewing construction professionals in the industry and built and validated using Protégé software as shown in Figure 4.

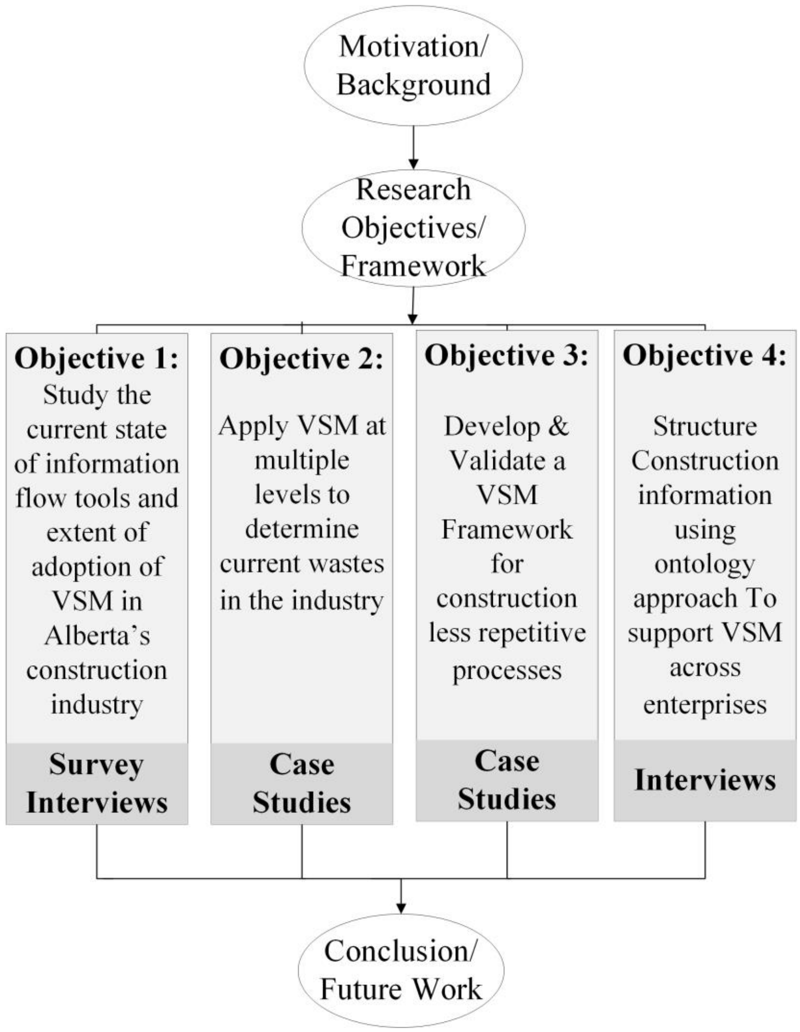

Figure 4: Research Framework

Chapter 3: Survey and Interviews

To determine the existing information flow tools currently used in the construction industry as well as process improvement tools, surveys and interviews are conducted.

The data obtained was collected via a cross-sectional survey in the fork of a questionnaire developed using Google Forms and distributed through the Edmonton Construction Association (ECA) e-newsletter, [161]. A survey was chosen as the preferred approach because the study is seeking to describe a reality, [156]. The questionnaire aims to determine the existing tools used by individuals and enterprises to exchange information in Alberta's construction industry. ECA is the largest non-profit construction association in western Canada and serves all construction sectors, i.e., residential, commercial, institutional, and industrial. The association membership is made up of over 1,300 Edmonton-area firms, including trade contractors, manufacturers, general contractors, suppliers, owners, architects, engineers, and associated members, [161]. The survey is divided into five sections. In the first section, participants were asked about their roles and experiences in the industry to understand their professional background. The second section focused on the tools that are currently used to exchange information in construction projects. In the third section, questions were asked about the tools and methods used to exchange information during specific phases of the project, e.g., procurement, tendering, etc., where multiple partners are involved. In the fourth section, participants were asked about *key performance indicators* (KPI), including information management KPIs. The last section focused on determining if any tools or techniques are currently being used to improve efficiency including lean management tools.

The survey is sent via the ECA e-newsletter twice, in March and April 2018. 16 completed answers are received from the 1300 members who received the e-newsletter. The response frequency provides a 95% confidence level with a confidence interval of 24.36%, [162]. The low response rate is a major limitation and would not allow the generalization of the results. However, responses received from various construction stakeholders i.e. project owners, contractors, subcontractors and consultants who work in all major construction sectors, i.e., residential, industrial, commercial and infrastructure. Most of the participants have more than 5 years of experience as shown in Figure 5. Participants were not asked about their genders because the focus is on their work experiences and the construction sector they are working in. Therefore, no gender-based results are in the survey. The results are not deterministic because of the low response rate, but still insightful due to the participants' profiles that can be a representation of the industry. The results indicate the extent of adoption of VSM in Alberta's industry, but a larger sample size will be required for a narrower confidence interval.

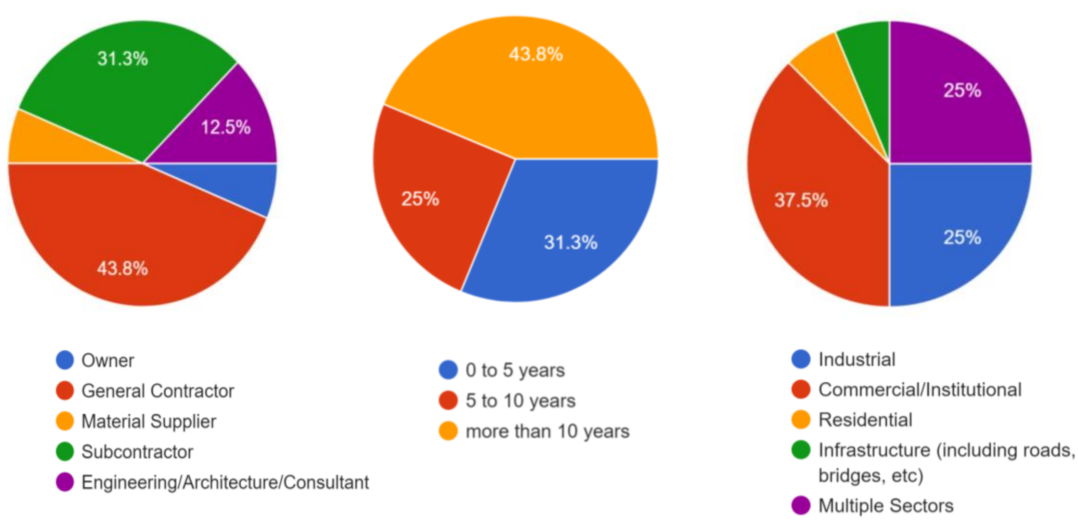

Figure 5: Information Flow Tools Survey Results- Participants

3.1 Survey Results

There were several tools and methods of communication stated by the participants; these included meetings, phone calls, face to face discussions, emails, correspondence via hard copy, and information management systems (IMS). The respondents were requested to select the frequency for each tool's usage on a scale of 0 through 4, as follows: never (0), seldom (1), sometimes (2), often (3) and always (4). The frequency index for usage (I_F), frequency index for sharing and storing information (I_S), and importance index (I_I) are calculated using equations (1)–(3), respectively, [163]. I_F is used to rank the information flow tools based on frequency of usage as identified by the participants while I_S used to rank the socialization of information for each tool based on the frequency of storing and sharing information as identified by the participants as shown in equations (1) &(2) respectively, [164]. The importance index is calculated as a function of I_F & I_S as shown in equation (3).

$$I_F = \frac{100}{4N} \sum_{i=0}^{i=4} n_{Fi} \, x \, d_{Fi} \qquad (1)$$

$$I_S = \frac{100}{4N} \sum_{i=0}^{i=4} n_{Si} \, x \, d_{Si} \qquad (2)$$

$$I_I = I_F \; x \; I_S/100 \qquad (3)$$

Where,

n_{Fi} = Number of respondents who indicated that they used the communication approach in question at a degree of i. (e.g., if 10 respondents said they use email "sometimes", then n_{F2} =11 for email).

d_{Fi} = Degree of use indicated by the respondent for communication approach in question (e.g. if the respondents mentioned they use email "sometimes", then d_{F2}=2)

n_{Si} = is the number of respondents who indicated they share, and store information communicated using the communication approach in question at a degree of i (e.g. if 6 respondents said they "always" share and store information communicated by email then n_{S1} = 6).

d_{Si} = Degree of sharing and storing information indicated by the respondents for communication approach in question (e.g. if the respondents mentioned they "sometimes" share and store information communicated by phone then d_{S2}=2).

N = is the total number of respondents.

I_F shows that email is the most used method for communication, followed by meetings, phone calls, correspondence, and IMS, respectively as shown in Table 2. The participants were also asked about the efficiency of emails in communication, with over 70% of the responses indicating that they experience late replies for requested information via emails, which causes delays in making decisions. Only 12% indicated that email is an effective means of communication, encountering no delays.

Table 2. Information Flow Tools - Frequency index for usage (I_F)

Communication Method	I_F (%)
Emails	91
Meetings	80
Phone calls & face to face discussions	69
Correspondence (hard Copies)	56
Information Management System (IMS)	31

Knowledge is one of the essential assets in the construction industry because of its role in innovation and value creation, [165]. Knowledge is divided into tacit and explicit knowledge. Explicit knowledge is stored and can be shared in the form of data, Figures, etc., where tacit knowledge is deeply rooted in individuals' behaviours and has to be learned through interactions, [166]. An interview is an effective research method to collect tacit knowledge, [153]. The interaction between tacit and explicit leads to knowledge creation. A four-stage conversion model known as SECI (Socialization, Externalization, Combination, and Internalization) is built to show the steps of converting tacit knowledge to explicit and ultimately knowledge creation, [167]. The first step, socialization, is where information is shared at the individual employee level through various means of communication. At the externalization stage, tacit knowledge is transformed into formal knowledge that is stored and shared in a formal language such as figures, charts, manuals, etc. The third stage, combination, is where explicit knowledge is placed into a systematic structure. Finally, the fourth is internalization, where individuals absorb the explicit knowledge and create their tacit knowledge, [168]. Based on the SECI model, tools and means of communication are crucial for knowledge creation and for transferring tacit knowledge into explicit knowledge. Furthermore, socialization and externalization are highly dependent on the means of communication utilized.

The participants were asked about the frequency of storing and sharing information communicated by emails, meetings, phone calls and face to face discussions. As shown in Table 3, the I_S for emails is 72%, while it is 55% for meetings and 19% for phone calls. Considering that emails, meetings, phone calls, and face to face discussions are the most common means of communication used in the Alberta construction industry, with minimal use of IMS, we can conclude that a sizeable amount of exchanged information not adequately socialized or externalized and remains at the individual employee level. This hinders knowledge creation which adversely impacts innovation and value creation.

Table 3. Information Flow Tools Survey Results -Frequency index for sharing and storing information (IS)

Communication Method	I_S (%)
Emails	72
Meetings	55
Phone calls & face to face discussions	19
Correspondence (hard Copies)	N/A
Information Management System (IMS)	N/A

The importance index for each tool was calculated based on the frequency of usage as well as the information storage and sharing frequency index, with results shown in Table 4. Emails have an important index of 65% while phone calls and face-to-face discussions scored the lowest at 13%. Taking into consideration the usage, storage, and sharing frequency factors, the current tools for information flow in Alberta's construction industry is not as effective as it could be and doesn't support knowledge creation based on SECI model. The study results are in accordance with similar studies completed in other regions where the construction industry faces similar challenges in terms of inefficient communication and loss of information, [169]- [170]- [171]- [172].

Table 4. Information Flow Tools Survey Results- Importance index (II)

Communication Method	I_I (%)
Emails	65
Meetings	44
Phone calls & face to face discussions	13
Correspondence (hard Copies)	N/A
Information Management System (IMS)	N/A

Approximately 56% of the respondents use hard copy purchase orders to procure materials while the remaining use different tools such as emails, phone calls, internal systems, etc. The answers show that existing tools used to exchange information in the procurement supply network in Alberta are project or company dependent and unstandardized. The answers are in accordance with the case study results where the construction industry is relying on hard copies, phone calls, emails to exchange information for procuring materials.

3.2 Survey Results: Key Performance Indicators

One of the steps in developing the VSM is the selection of the process metrics, such as the processing time, information management tools, crew size, to measure the performance and efficiency of the process and associated activities. The participants in the survey are asked to identify the importance of safety, customer satisfaction, productivity, quality, waste reduction, performance, cost, information management and safety *key performance indicator* (KPI) as shown in Figure 6. Safety KPI is ranked by the participants as the most important to their organizations.

Cost reduction, customer satisfaction, and schedule ranked the second, third and fourth important KPIs respectively. The participants were also asked if they have a KPI to measure the process improvements within their organization i.e. increasing the efficiencies of the processes. These results are in accordance with other studies that show time, quality, cost, and safety are the top performance indicators established in the industry, [173]. These KPIs are considered traditional lagging KPIs that are based on safety, cost and customer satisfaction. Enabling Construction 4.0 will require the industry to adopt more leading KPIs, such as data quality, customer return rate, not just only the lagging traditional ones, [49] Moreover, these traditional construction KPIs have limited use during the execution phase and need to be replaced with active performance indicators to improve project controls, [174]. The survey results show Alberta's construction industry is still using the lagging KPIs which is in accordance with the other studies. This is may hinder developing VSM across enterprises because of the plack of agreement on leading KPIs that can be successfully used to monitor and adjust future state maps among various stakeholders (if needed).

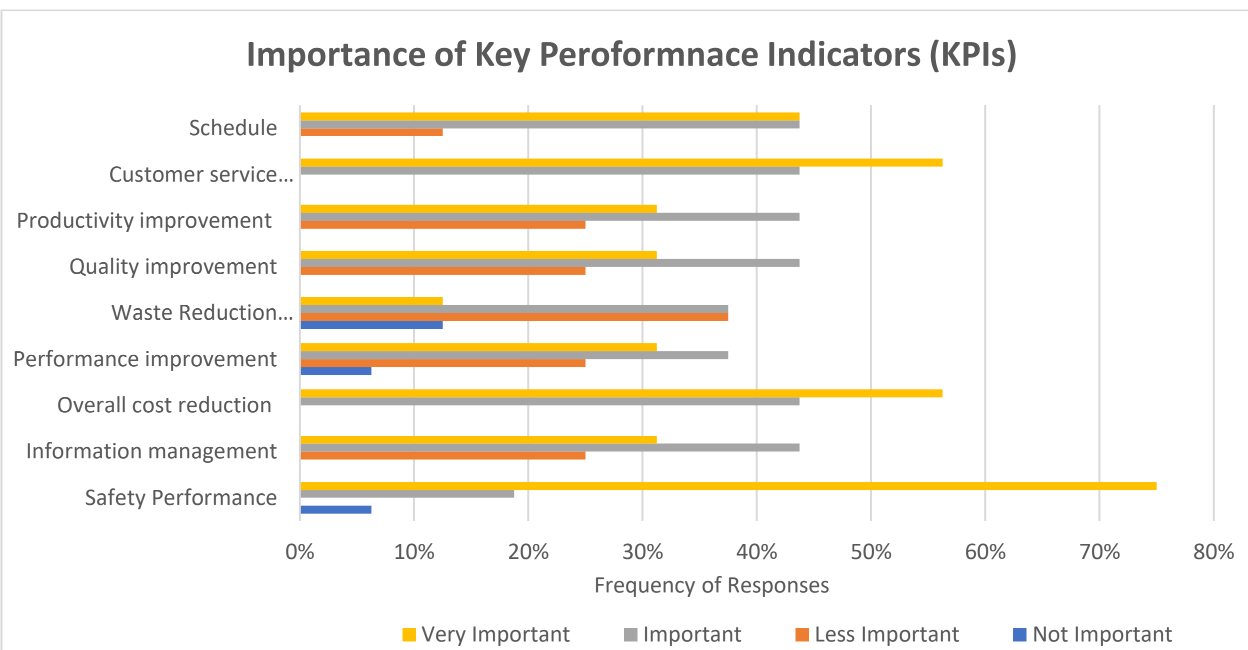

Figure 6: Information Flow Tools Survey Results - Importance of KPIs

3.3 Interviews

Five semi-structured interviews are conducted with professionals who are in mid-to-senior level management positions within their organizations. The validity and reliability of the collected data is within a constructivist paradigm, not a positivist, [175]. Thus, results are not deterministic but still insightful due to the careful selection of interviewees that represent various companies within the Edmonton construction industry as well as their experiences. The interviews aim to determine the current tools and techniques managers use to improve processes and enhance efficiencies as well as the extent of adopting lean management tools in the industry. The interviewees are asked eight questions, related to (1) the interviewees' professional experience and current position within the organization, (2) the interviewees' familiarity with lean management tools, (3) their processes' wastes, (4) how they measure their processes' efficiencies, (5) tools and techniques they use to enhance their processes, (6) how they find the root causes of the problems they encounter in their workplace, (7) how they measure the value of the products and/or services they deliver to their clients, and (8) whether they implement VSM to identify and eliminate wastes to increase their values.

The interviewees work for four different organizations and their current positions are Vice President, Project Director, Senior Planning Engineer, Safety Director, and Senior Project, Coordinator. The interviewees work in various departments within their organizations. Three of the interviewees mentioned that they are not familiar with lean management tools and the other two stated they are familiar with them, but they haven't used them at work. Only one interviewee is not familiar with the process wastes, but the others mentioned that they have at least some familiarity with some types of wastes. All interviewees mentioned that they don't measure their processes' efficiencies, but they measure local productivities which are mainly related to the cost and productivity of certain activities. Likewise, they don't measure any KPI's for the value stream of these activities.

Four of the interviewees stated that they haven't implemented any tools or techniques that can improve their processes' efficiencies. One interviewee discussed using previous experiences to improve current processes, but they have no procedures or tools to implement those improvements. All interviewees mentioned that they investigate and analyze safety incidents to find their root causes, however, those investigations or analyses haven't been extended to other departments. Only one interviewee stated that he uses the 5-why's technique in the root cause analysis, but the remaining haven't mentioned any tools or techniques. Two of the interviewees stated that they don't measure or evaluate the value of the product or service they deliver to their customers, while the other four interviewees talked about qualitative analyses, such as "repeat business" and "discussions with clients", which they use to gauge customer satisfaction. None of the interviewees have used VSM in the workplace.

The results show that most of the interviewed managers are not familiar with lean management tools, including VSM. Moreover, they have not implemented tools or techniques that can identify and eliminate wastes, increase process efficiency, and deliver better values to their customers. Despite the benefits of lean construction in terms of eliminating wastes and improve efficiencies, studies show that it hasn't been widely adopted in the industry due to many barriers that are still facing its implementation, such as lack of education and investment costs, [176], [61], [177]. Lack of awareness and unfamiliarity with lean are major barriers in adopting it, [178]. The results of these studies are in accordance with the interview and survey results we conducted in Alberta that lean has not been widely adopted in the industry yet

3.4 Survey and Interviews' Conclusion

The survey results, based on the participants' answers, show the construction industry in Alberta uses many tools to exchange information inconsistently. The information is most likely neither shared nor stored and poorly communicated. Most of the information seems to stay at the individual levels which can hinder knowledge capitalization. Moreover, the importance of KPIs varies among companies which is promoting the fragmentation of its supply chain as each organization works to achieve its own goals. VSM is an efficient tool that has been adopted by the manufacturing industry to identify and eliminate wastes. However, the construction industry in Alberta seems that it has not adopted VSM yet. The survey results are compared to similar studies that were conducted in other regions, using criterion validity test, [179]. A study conducted in the UK shows emails, meetings and hard copy documents are the most common approaches to communicate information at the construction site level, and information is not exchanged properly, [180]. Studies completed in various regions show that the industry relied on meetings, face to face discussions, emails, and phones to exchange information, [181]-[182]-[183]-[184]. The results of other studies also show that e construction industry faces challenges in terms of inefficient communication and loss of information, [169]-[170]-[171]-[172]-[185]. The survey results we conducted in Alberta are in accordance with these studies in terms of the tools to exchange information as well as their inefficiencies.

Chapter 4: Case Studies – VSM

Construction project consists of several phases which include project definition, design, installation, operation and maintenance phases as shown in Figure 7. Project owners, engineers, consultants, contractors, material suppliers and subcontractors collaborate through the various phases of the project, [38]. During the project definition, the project owner (client), engineers, and architects work together to define project concepts, feasibility study and shaping the project. In the next phase design phase, engineers with various disciplines such as mechanical, electrical and civil work together to design the project. After design is complete, construction contractors build the project and turnover it to the owner who operates and maintains it as shown in Figure 7. In the procurement stage, the owner usually hires a contractor to manage and perform the work. The project's materials and equipment are also purchased during this phase, [38]. Procurement processes involve many partners such as owner, contractor, suppliers and subcontractors which requires information and/or material flow across enterprises. The study implements VSM at the nano and meso levels in procurement and tendering case studies to understand the current state of the industry in terms of improving its performance by identifying and eliminating wastes.

4.1 Procurement VSM Case Studies

VSM is implemented in procurement case studies for two different projects. The projects' scope of work includes fundamental construction activities for earthmoving and concrete foundations. The study examines onsite procurement activities. Data is collected for six cases from the two different projects by field observations, using ERP system database, and projects' documents. The durations of the cases vary from 192 to 450 hours. VSMs are developed at the Nano level and links

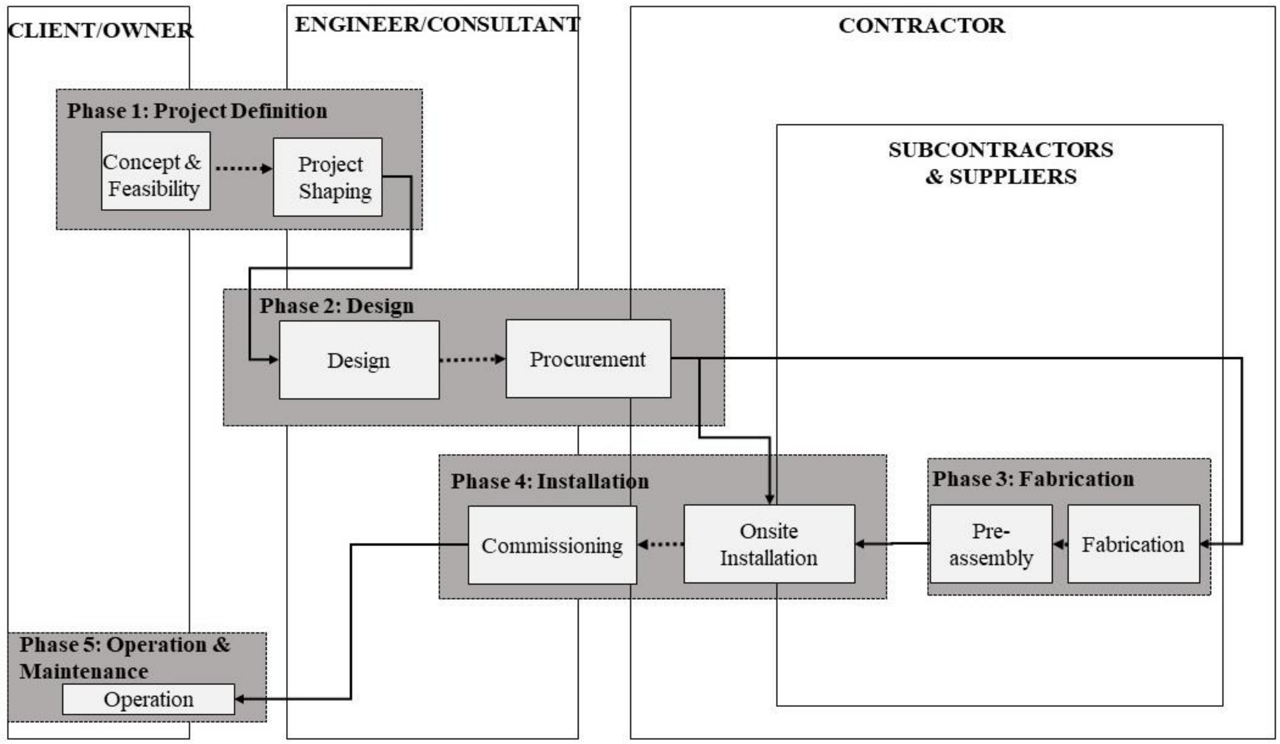

Figure 7: Construction Project Phases (adapted from [186])

are shown to the meso level. After analyzing the current state map and implementing lean management techniques, a future state map is developed, and recommendations are made to overcome some of the industry's challenges. The General Contractor (GC) is responsible for executing the scope of work which includes earthmoving and installing concrete foundations. GC hires several subcontractors to perform specialized work and purchase materials from local suppliers. The study focuses on material procurement activities which include calculating quantities, ordering, shipping, and installation of materials. The two projects have different management teams and clients. Construction materials are specified on design drawings by design engineers. Procurement and installation of materials are executed by GC's site team i.e. project engineer and superintendent. The material's cost was determined during the tender stage by GC's estimators and carried in the project's cost estimate. However, the site teams request several quotes before ordering the materials in an attempt to find more competitive prices. Material costs may vary between the estimate and installation times due to changes in market conditions. Therefore, checking material prices is important especially for long-term projects where the project's schedule extends over several years. The VSM is completed as per the following steps:

Step 1: Identification of customer needs

The customer, i.e. project owner, requires the material to be supplied and installed as per design drawings and specifications at the lowest possible cost.

Step 2: Main Process Identification

The project requirements are outlined by the project's owner. The project is designed by the engineers who specify the materials and design requirements. Then, design drawings and specifications are transferred to the construction contractor who purchases and installs the materials.

Step 3: Selection of Process Metrics

Following are the chosen metrics to measure process efficiency:

- Time including process and lead times to identify value-added and non-value-added times,
- Activity Ratio which is the percentage of process to lead time,
- Information technology used for information flow i.e. ERP system, email, phone calls, paperwork to identify information flow tools,
- Queues or wait time that the information was held on someone's desk without being processed,

- Personnel performing the work.

These metrics measure the efficiency and duration of the activities, show the information flow tools, and the personnel who are performing the activities to understand the roles of each partner within the supply subnetwork.

Step 4: Creation of the Current State Map

The current VSM is developed as shown in Figure 8. It shows that the construction industry relies on phone calls, emails and hard copies to exchange information. The hard copy purchase order is an inefficient information flow tool. It was held onsite for several days which hinders the execution of the next step, creating a long queue. Moreover, it creates no value to the process as it is only a "middle" step before the information is transferred to the ERP system.

The materials are purchased and delivered to the site several weeks before installation. Therefore, the "just in time" technique hasn't been implemented which adds extra cost for storing and handling the material. This is common in all six cases where materials were ordered in advance and stored onsite. The contractor orders the materials in advance to ensure they are available once needed without considering the extra cost and wastes associated with early material purchasing.

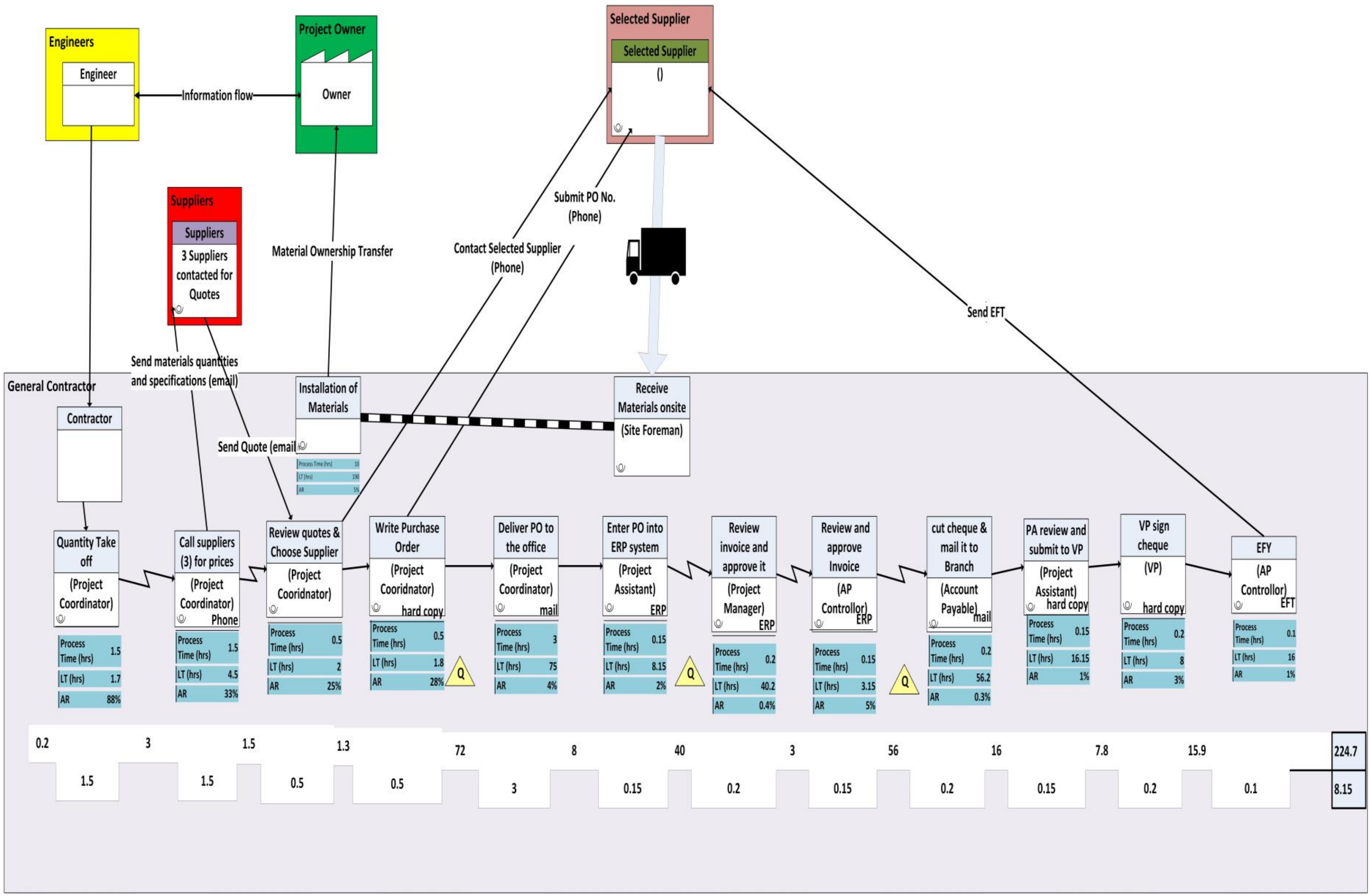

Figure 8: VSM Case Study- Current State Map

Step 5: How can we create an improved future state map?

The following steps are completed to develop the future state map:

(a) What does the customer need and when?

The customer i.e. the project's owner requires the materials to be purchased according to design drawings with the lowest price and installed on time to meet the project's milestones.

(b) Which steps create value, and which ones are waste?

The current state map shows owners, engineers, contractors and suppliers are operating in an "island" concept i.e. fragmented supply chain where every partner works on his own. At the Nano VSM level, the following wastes can be identified:

- Extra processing: there are four approvals for the suppliers' invoice
- The physical transportation of the PO to the office is a waste and increased the queue for the process
- The physical mailing of the cheque to the office
- Overproduction: extra work has been created by the hard copy PO system which creates no value to the process.
- Waiting: The project assistant was waiting for the PO to process the data in the ERP system.
- Inventory:
    - Invoices are processed randomly, so the number of POs is fluctuating in the system.
    - Materials are stored and preserved on site before they are installed, so extra unnecessary inventory is created.

(c) How can we increase the workflow with fewer interruptions?

Examining the contractor activities, the PO was queued onsite at the project coordinator's desk for almost two weeks which interrupted the value stream of the process and did not allow the next step to occur. In a "push system", the PO should be delivered to the office immediately after it has been issued to the supplier which can be completed by mailing it or sending a scanned copy. However, a more efficient approach can be achieved in combining and eliminating activities as shown in Figure 9.

"Just in time" pull system can be implemented at the site level for purchasing materials, so materials are ordered only when needed. This reduces inventory and material handling times. Moreover, it can support the company's cash flow by making payments for materials only once needed. Such a system can prioritize the next steps in the procurement value stream by processing payments based on FIFO and reduce the amount of work in process (WIP). The more WIP and in queue in the system, the longer it takes to process the work. By controlling the time of ordering material based on "due date" i.e. when needed as per the construction project schedule, the size of the queue can be reduced which results in a more stable and predictable value stream. Implementing the "Just in Time" model for purchasing materials can reduce costs by minimizing the space and effort needed to store and preserve them.

To increase workflow within the subnetwork, a collaborative supply chain can be developed where all partners can communicate effectively throughout all phases of the project.

(d) Create Future State Map

Using the analysis in previous steps, a future state map is developed as shown in Figure 10. The process and lead times are calculated and compared to the current state values as shown in Table 5. Process time has been improved by 43% i.e. 3.5 hours. Taking into consideration the company processes hundreds or thousands of invoices annually, this is a significant cost reduction which reduces the overall project cost and creates value for the customer. Moreover, more cost reduction can be achieved by implementing "just in time" for ordering materials on site by reducing or eliminating storage and inventory cost. Besides, collaboration and partnership with the suppliers can increase process efficiency by eliminating the request of extra quotes from several suppliers.

Table 5: VSM Case Study- Current Vs Future VSM Summary

	Process Time (hrs)	**Wait/Inventory Time (hrs)**	**Lead Time (hrs)**
Current State Map	8.15	224.7	232.85
Future State Map	4.65	181.2	185.85
Improvement	43%	19%	20%

4.2 VSM Tender Case Study

Tendering is a procurement process where the project owner or his representative invites construction companies to bid on a project. A case study for a tendering process is completed. The contractor was invited to bid on a project. The project's scope includes excavation, backfill, dewatering and installing a liner.

The current state and future state maps are developed, refer to Appendix B for the VSMs. After implementing lean management tools, the processing time for future state maps is improved by 23.19 hours i.e. 23.19% as shown in Table 6. This is a significant cost reduction taking into consideration the company develops many proposals annually. This improvement is achieved at the enterprise process level i.e. nano level. However, significant improvement can be achieved at

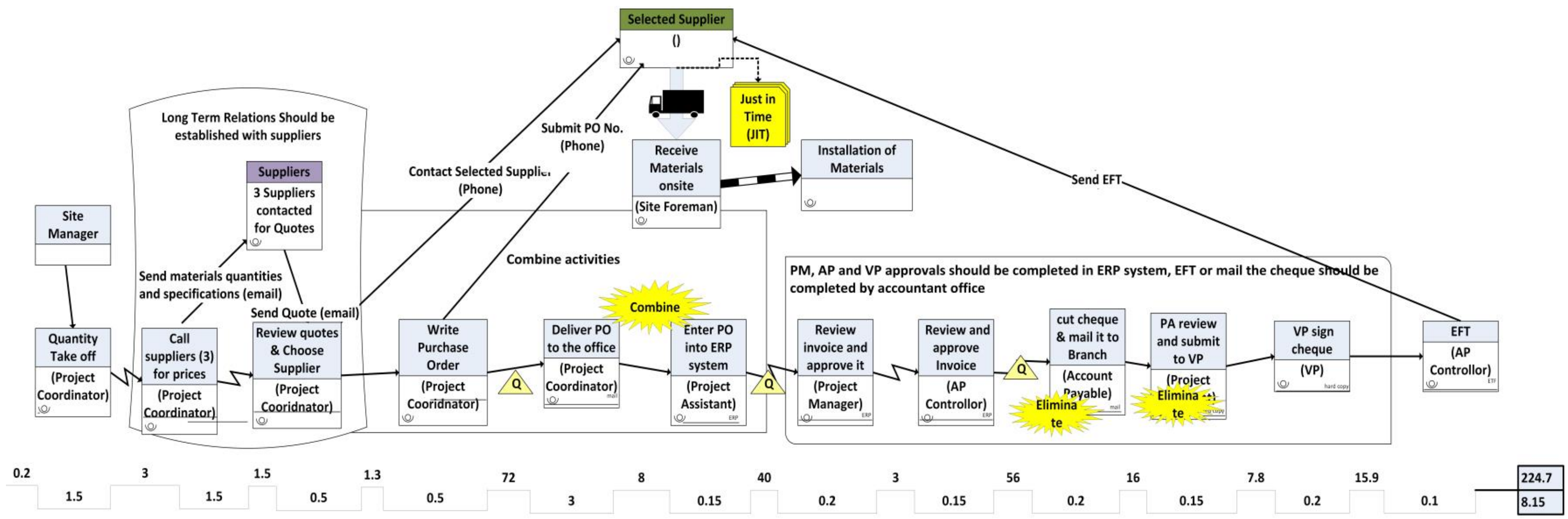

Figure 9: VSM Case Study - Current State Map Comments

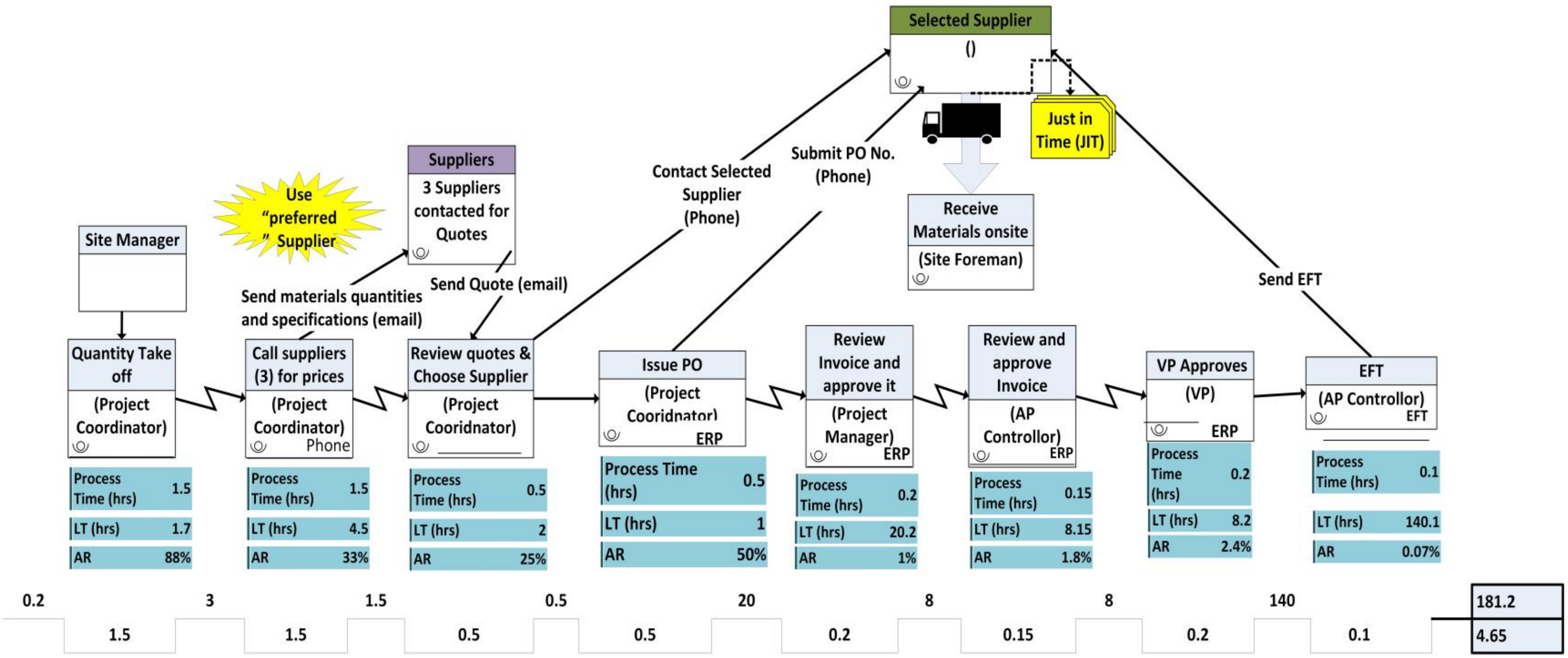

Figure 10: VSM Case Study - Future VSM

the subnetwork level by completing Meso VSM and implementing an information management system that can be adapted by all stakeholders.

Table 6: VSM Case Study- Tender Case Study Results

	Process Time (hrs)	**Non-Value-Added Time (hrs)**	**Lead time (hrs)**
Current State Map	86.25	58.5	144.75
Future State Map	66.25	12.5	78.75
Varinace (hrs)	20	46	66
Varinace (%)	23.19%	78.63%	45.6%

4.3 VSM Case studies Discussions

The data was collected for the other five procurement case studies from two different projects. The processes for all the cases are similar i.e. the site team calculates the bill of quantities, calls multiple suppliers to request pricing, issues a purchase order for the supplier with the lowest price then send it to the office where the account payable department follow the same process to pay the supplier. The developed future state map is applicable to all the cases. On the other hand, data was collected for a second tender case study, and it was noticed the company follows the same process i.e. the estimators lead it and many review meetings with the managers are conducted to finalize the estimate. The future state map that was developed for the first tender case study is applicable for the second one. Based on mapping the procurement and tender case study, it was noticed that implementing VSM in one case study for the replicated process can be sufficient even though the stakeholders are different. Construction companies can improve their processes significantly by implementing VSM at the nano and micro levels.

The process time in the procurement case study is improved at the nano level by 43%. However, meso VSM that maps the entire procurement subnetwork can introduce a global optimization to the process along the value chain network. This will promote the integration of the supply network where information can flow efficiently among the project's partners. An efficient information management system not only can reduce the project's cost but also improve quality by providing accurate and on-time information. Following are recommendations to overcome some of the construction supply chain challenges based on case studies' results:

- The construction supply chain is temporary**.** The case studies show that contractor- supplier relationship is temporary and on a project-to-project basis where the contractor contacts several suppliers before purchasing materials. A long-term relationship may minimize the impact of this challenge. The nature of the construction industry is project-based i.e. temporary, but the relationship between contractor and supplier can be permanent, so material for different projects can be purchased from the same supplier. Such permanent relation can build trust among the project's partners and enhance communication which can improve efficiency and performance. Meso VSM can support the development of a standardized framework where partners can collaborate in a permanent partnership.
- Construction is a conservative industry driven by cost. The contractor tries to obtain the lowest material prices even though this may have cost more through the "waste" and extra steps created in the process. Moreover, the industry is still heavily dependent on paperwork and hard copies such as PO, mail, and cheques. The contractor has an ERP system, but it's not fully utilized. To reduce costs and have a more efficient process, ERP and other technologies should be adopted throughout the whole process. Macro VSM can support

integrating supply chain and standardization as well as introducing new techniques to improve the entire supply chain.

4.4 Case studies Conclusion

The case studies for procurement and tendering processes involve many partners i.e. general contractors, suppliers, subcontractors, engineers and project owners. The results show inconsistency in the tools used for information flow among stakeholders i.e. emails, hard copies, web-based systems, etc.; every partner uses his tools which promotes the fragmentation of CSC. The inconsistency also creates wastes due to "wait" and extra processing. Moreover, the case studies show that the construction industry hasn't yet adopted lean management tools to enhance efficiency even at the nano or micro-levels. VSM at the nano level partially enhanced the process by eliminating waste at its level. However, major improvements can be achieved by a VSM at the meso and macro levels i.e. across enterprises. The key to implement multilevel VSM in CSC is information management to ensure information is flowing efficiently among all partners and across enterprises. The future VSM can be implemented in CSC repetitive processes such as office and administrative ones. However, the current VSM methodology may not be efficient for non-repetitive processes as the future VSM most likely would not be executed.

Chapter 5: VSM Framework in Construction

VSM is an effective tool in replicated processes by identifying wastes and inefficiencies in the current state map and implementing the improvements in the future state map. However, taking into consideration the characteristics of the construction supply chain i.e. projects are built as per owner requirements, every project is unique, the temporary supply chain that involves a large number of partners in nonrepetitive processes and uncontrolled environment [29], the current VSM methodology can be inefficient for onsite construction processes. The study proposes a framework to implement VSM during the planning phase of the project, pre-construction activities, and utilize it as a monitoring and controlling tool during the execution phase.

5.1 VSM Framework

VSM aims to create graphical representation for the current processes, to identify and eliminate wastes, aiming to create a better value for all stakeholders. The study proposes a framework that incorporates VSM during the project planning phase of a local construction project, and use the developed plan to monitor it during the execution phase. The intent is that it will allow the project team to identify and eliminate wastes before execution, and measure and control performance during the subsequent execution phase. The proposed framework has three VSM's compared to two in the traditional methodology. In our proposed framework, the first map represents the current planned processes. Wastes are then identified and eliminated, to develop the "planned VSM" (PVSM). The third map is developed to monitor the execution phase, update any future PVSM's, and compare actual process metrics to those that are planned. The third VSM also forecast remaining activities based on completed activities' performance and allows the project team to monitor the project's progress and adjust the execution plan accordingly.

The developed framework has twelve main steps, as shown in Figure 11. The first step, (1), is to identify the client's needs, which establishes the value that the project's partners should work to create. In construction projects, the customer can be the project owner, internal customer, subcontractor, or supplier. The client can be identified as the one who accepts completed work. As an example here, the client's need for a concrete placing subcontractor might be triggered by the steel reinforcing installers completing their work on time and as per design drawings. The second step, (2), is the mapping of activities and their sequence beginning when the customer order is received, and running to the delivery of the final product or service. One of the major sources of information for this step is the "pull" planning session, which is a collaborative planning approach that involves all processes' stakeholders, [187]. Other tools can be used to identify construction activities, such as the project schedule, path of construction (which shows the sequence of project activities), project estimates, and construction execution plan. The third step, (3), is choosing proper process metricsmetrics to measure performance. The process metrics metrics should be chosen from the customers' perspective to meet their requirements and needs. For example, the process metrics for a concrete-placing process might be process time, crew size, lead time, and information flow tools. Process metrices should be chosen to reflect the execution plan; for example takt time is used to determine the duration of the product in an assembly line to meet demand; takt time may not be required to measure the process performance in some cases. Process metrices are specific for the process. The fourth step, (4), is the creation of the current state map for the process, which represents the current plan. The map should be validated with all stakeholders to ensure accuracy. In the fifth step, (5), non-value-added activities are identified. Waste is eliminated in the sixth step, (6); there are seven types of wastes as defined in the Toyota Production System: *overproduction, waiting, transportation, extra processing, inventory,* *movement, and defects*, [56]. These wastes can be eliminated by applying lean management tools such as *just-in-time*, *pull planning*, and *Kanban*, [57]. In the seventh step, (7), the constraints that may interrupt workflow should be identified and removed to ensure no workers are waiting for work and no work is waiting for workers. In step eight, (8), the future PVSM can be created and validated with the project team. Future state VSM is a visual tool for project execution plan that shows the flow of work and information across multiple partners which can support creating a collaborative work environment. In step nine, (9), the future PVSM should be monitored during the execution phase to update the process metrics for completed activities. They are analyzed in step ten, (10), and developed into a forecast plan based on completed activities' performance in step eleven, (11). These steps will be repeated until all activities are completed to develop the final map that shows PVSM versus the actual process metrics in step twelve, (12). Steps 9 to 12 are additional steps to traditional VSM. They can support the monitoring and implementation of VSM as well as forecast remaining activities based on completed ones. Process metrices are actualized once associated activities are completed, then activites 5, 6 and 7 are repeated for remaining activities to forecast future work. This is a nonlinear process due to the required iterations and repeating steps during project execution. This frameworkprovides flexibility to adjust the plan and eliminate wastes as site conditions change which support value creation for the client. The framework i.e. the steps to complete VSM can be generalized, but the details of VSM such as activities, processes metrices are process specifics and cannot be generalized.

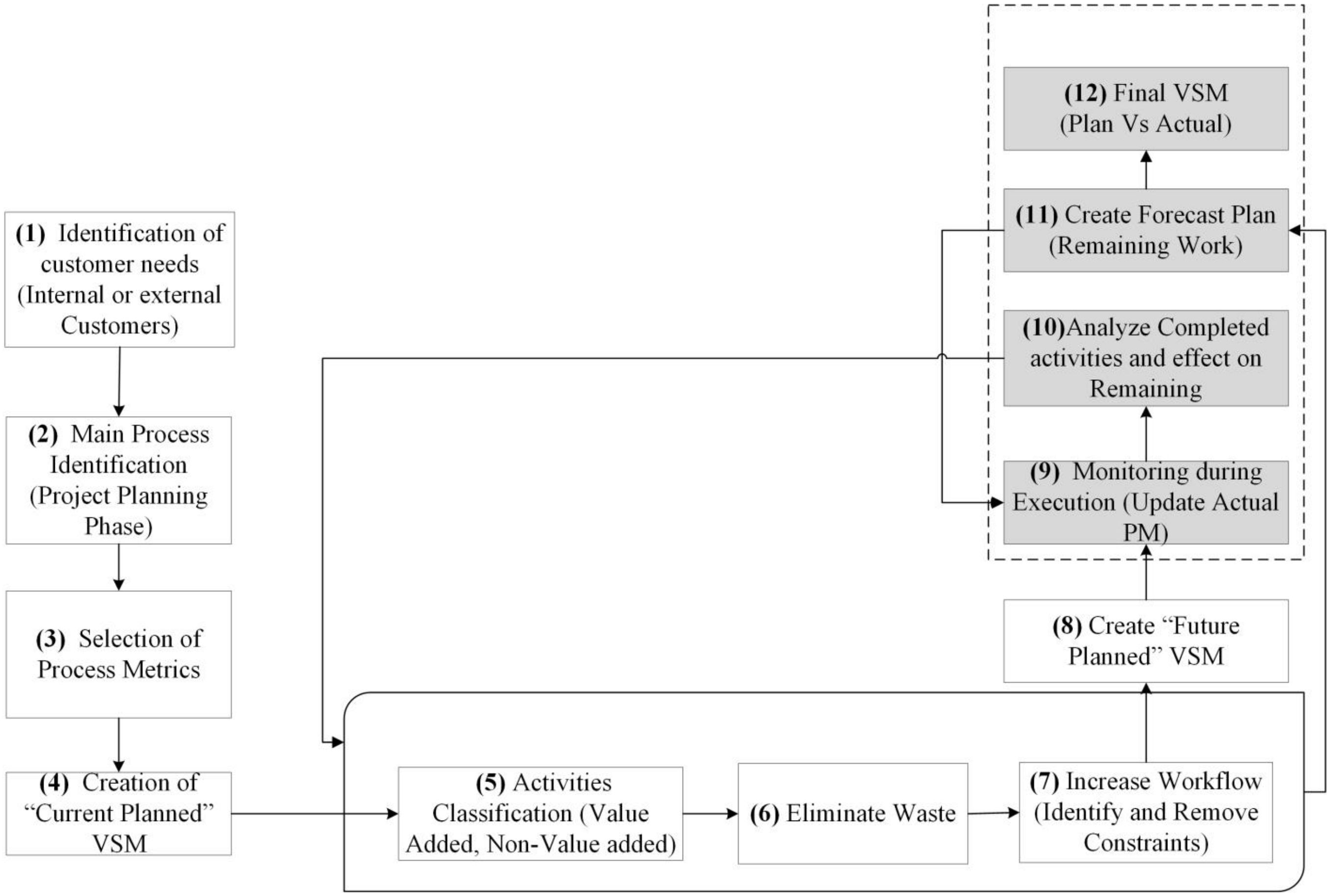

Figure 11: Construction VSM Framework (adapted from [52])

5.2 VSM Methodology: Case Study 1

This case study aims to demonstrate the developed VSM framework's concept. A typical site preparation earthmoving project is presented for a construction project team to prepare a project construction execution plan. The scope of work comprises topsoil stripping, general cut/fill, hauling of materials, and placement of backfill materials; bill of quantities is shown in Table 7:

Table 7: VSM Case Study 1- Bill of Quantities

Item	Description	UoM	Quantities	Comments
1	Stripping of Topsoil	m^2	60,000	Thickness 0.2-0.3m
2	Removal of Unsuitable Material	m^3	30,000	N/A
3	Haul unsuitable Material & topsoil to stockpile	m^3	45,000	1.5 km Haul distance
4	Granular Backfill- Placement	m^3	65,000	300 mm lift thickness
5	Granular Material-Load & Haul from stockpile	m^3	65,000	5 km haul distance

The project team developed a construction execution plan which requires five crews. Each crew consists of general labourers and equipment operators. Crews and equipment breakdowns are shown in Table 8. The project team anticipates 11 weeks to complete the work which includes mobilization, survey, construction and demobilization activities as shown in the project schedule in Figure 12.

Table 8: VSM Case Study 1- Crews and equipment list

Item	Description	Crew size	Equipment	Quantity
1	Stripping of Topsoil	5	Dozer (D8)	2
			40-Ton Excavator	1
2	Removal of Unsuitable Material	4	Dozer (D8)	2
			40-Ton Excavator	1
3	Haul unsuitable Material & topsoil to stockpile	5	40-Ton articulated trucks	5
4	Granular Backfill- Placement	6	Dozer (D8)	1
			Smooth Drum Packer	1
			Water Truck	1
			Grader	1
5	Granular Material-Load & Haul from stockpile	11	40-Ton Articulated Trucks	10
			40 Ton Excavator	1

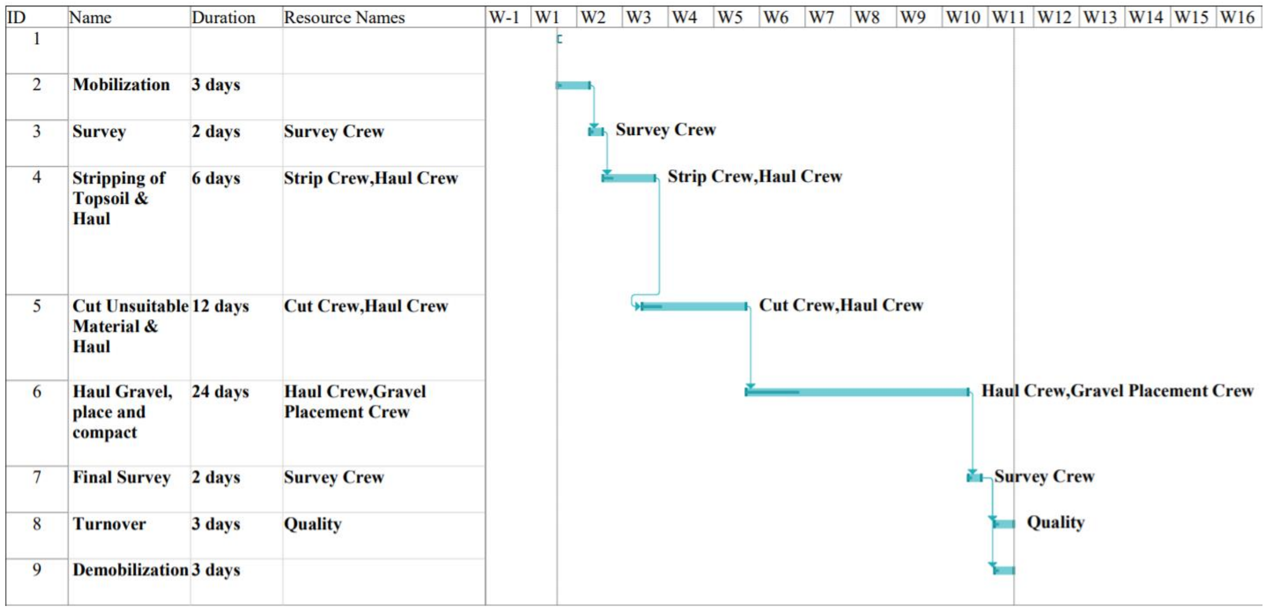

Figure 12: VSM Case Study 1- Project Schedule

The proposed VSM framework is implemented, using the following steps:

Step 1. Identify customer needs

The project owner needs the project to be completed within the project's budget at the lowest possible cost, on time, and as per design. Customer's needs can be achieved by hauling excavated materials and placing the backfill materials as per estimated productivities to maintain baseline project schedule as well as avoid cost overrun. The quality control team will monitor the backfill activities to ensure quality standards are met.

Step 2. Identify the process

The activities and resources such as equipment, crew size, and productivities are identified using the project's schedule and construction execution plan. Following is the sequence of activities: (1) the project starts with the mobilization activities, (2) topo survey to determine project limits and existing coordinates, (3) stripping and hauling topsoil, cut and haul unsuitable material, (4) haul and place gravel, (5) and finally survey placed materials and demobilization.

Step 3. Select Process Metrics

Process metrics are chosen to measure process time, wait time, lead time, Crew & Crew Size, productivities, cost, and quantities for each activity. These process metrics map the project execution plan as well as can measure its progress. The lead time show activities' durations which can be summed to determine the overall work duration. On the other hand, crew names and sizes as well as manhours show work execution and provide metrics that can be compared to the original plan and estimate.

Step 4. Develop Current VSM

The current VSM for the project execution plan is developed as shown in Figure 13. VSM is a visual tool for the project execution plan. It shows the project schedule, productivities, crews and their sizes, cost, and critical path which facilitates socializing the plan with the entire project team. The project is divided into three phases: (1) stripping/hauling, (2) excavating/hauling, and (3) hauling/placing. The activities of each should be completed concurrently. The VSM shows hauling topsoil and unsuitable materials as well as loading gravel are the project critical path activities. These activities have no float time. A critical path is the set of activities that determines the overall project's lead time, [188].

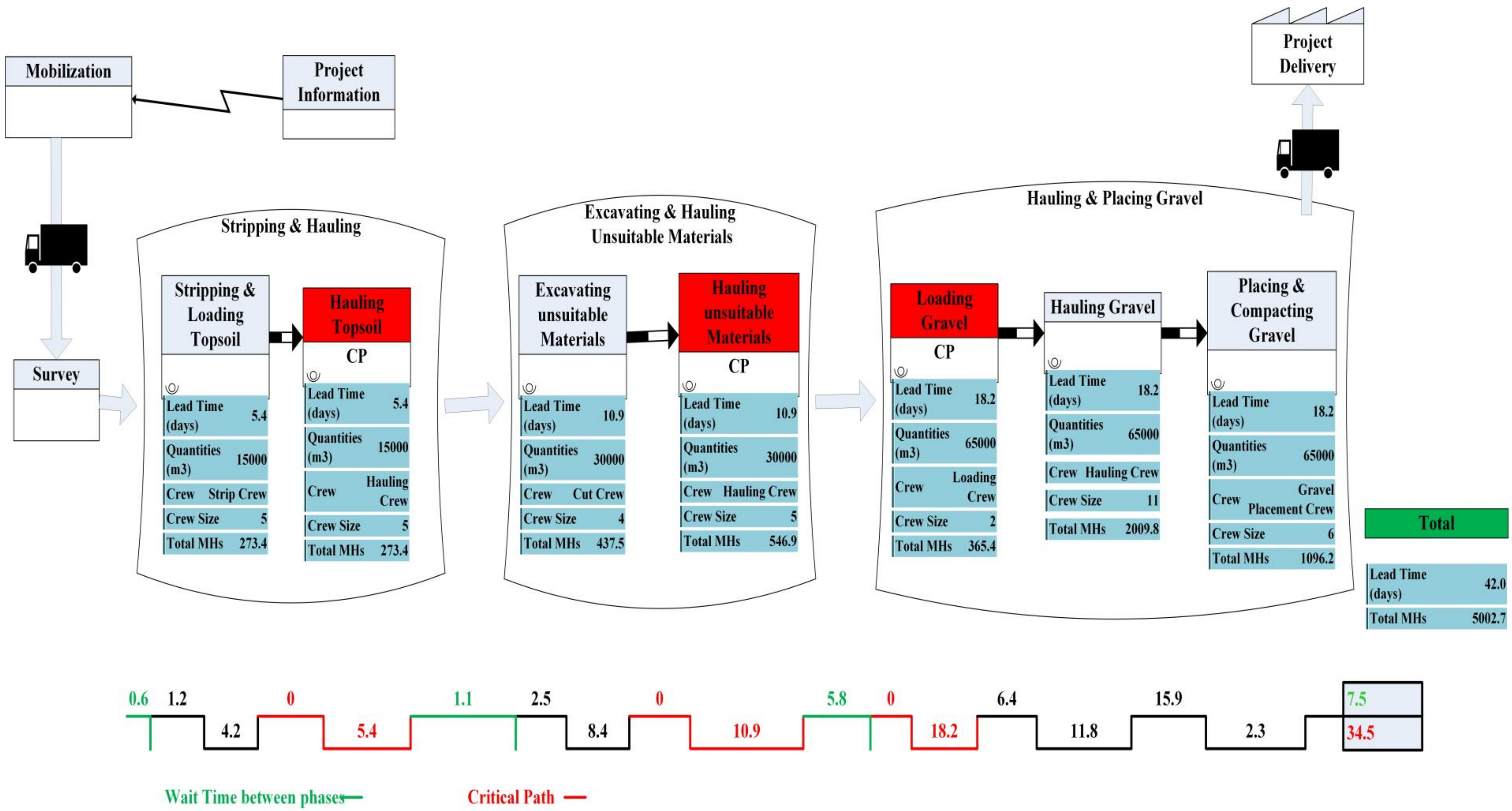

Figure 13:VSM Case Study 1- Current "Planned" VSM

Steps 5&6. Classify Activities to Identify and Eliminate Waste

Waiting is the major waste in the process and can be classified into two categories: crews waiting to start the work and work waiting for execution. The total wait time between the three project phases is 7.5 days as shown in Figure 13 which is a work waiting for execution. On the other hand, waiting times within the project phases are 1.2, 2.5 and 22.3 days for stripping & hauling, excavating & hauling, and hauling & placing gravel activities respectively. This waiting time is categorized as worker waiting to start work due to the fluctuation of the productivities and workload among working crews which is resulting in downtime.

Step 7. Identify and Remove Constraints to Increase Workflow

VSM shows the hauling crews have the most manhours. Therefore, increasing hauling crews' efficiencies and reducing their wait times can reduce the overall project's cost and duration**.** In stripping and hauling activities, the productivity for loading is higher than hauling, so process efficiency can be improved by levelling the workload between these activities via narrowing the gap between their productivities. On the other hand, a 40T articulated truck can be added to the hauling unsuitable material and hauling topsoil crews to increase their productivities from 342 m^3/hour to 411 m^3/hour which reduces the total wait time for these activities by 2.73 days. However, in gravel hauling crew, the productivities for hauling crew are higher than the loading crew which leads to 6.42 days of waiting time for the hauling crew. By decreasing the number of articulated trucks for the hauling gravel crew from 10 to 6 trucks, the productivity decreases from 685 m^3/hr to 411 m^3/hr which leads to having the hauling gravel as a critical path activity. This reduces the overall project cost as the hauling crew has the highest hourly cost.

Step 8. Create Future "Planned" VSM

The future state map is developed as shown in Figure 15. The wait time between phases is eliminated, and the resource levelling plan developed in step 7 is implemented. The project lead time and budgeted manhours are reduced by 20.4% and 12.5% respectively as shown in Figure 14. This is a relatively significant improvement for the execution plan. In future VSM plans, only hauling activities are on the project critical path as shown in Figure 15.

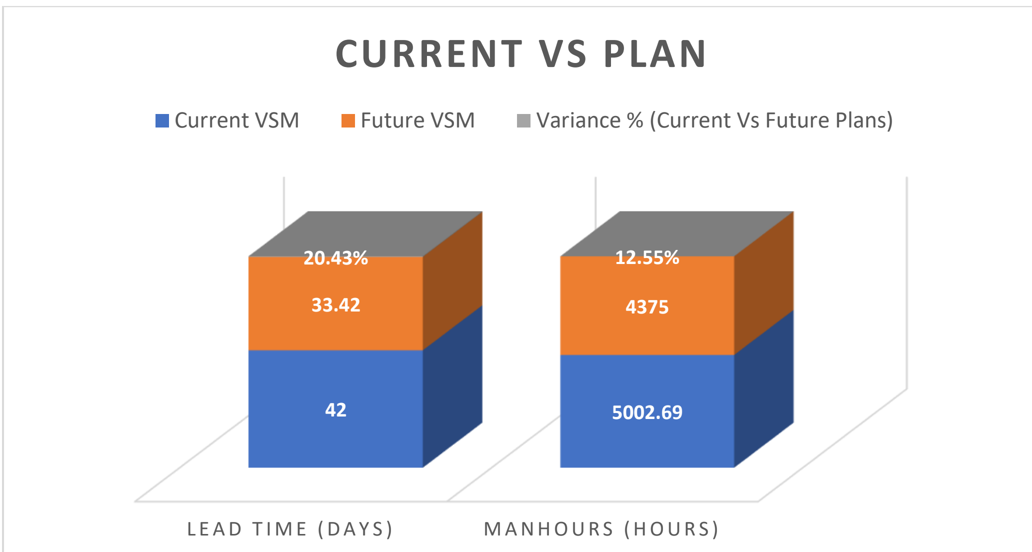

Figure 14: VSM Case Study 1- Current Vs Future Plan Results

Step 9. Monitor Future VSM

The planned future VSM can be monitored during the execution phase of the project, and process metrics such as productivities can be actualized for completed activities to compare actual performance to the baseline plan. This allows the project team to track performance and ensure

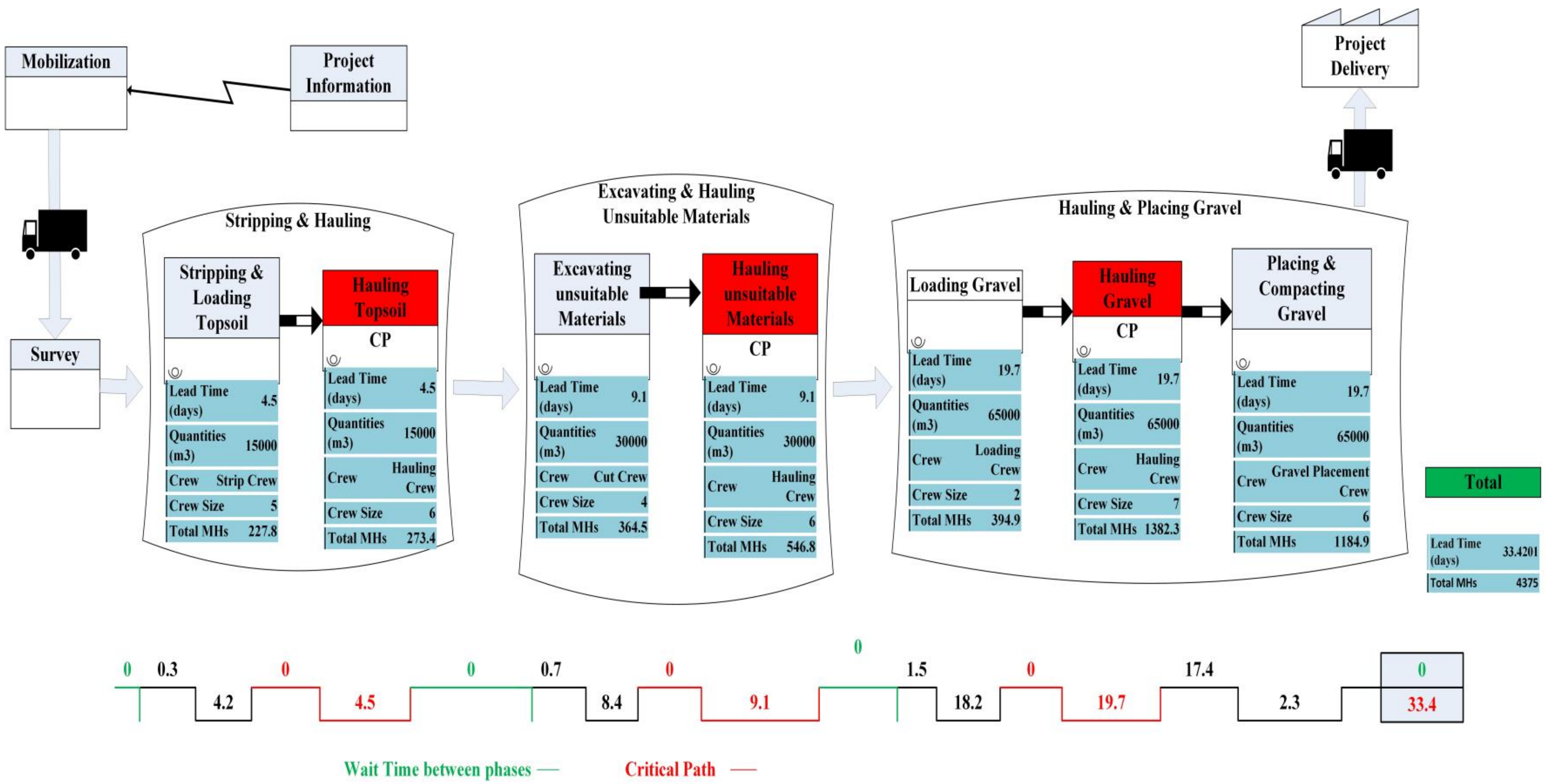

Figure 15: VSM Case Study 1- Future "Planned" VSM

work is progressing as per plan. Moreover, the project plan can be optimized (if needed) based on any unforeseen site conditions during the planning phase. Demonstration for an updated VSM is shown in Figure 16. A template for the to monitor the future planned VSM is developed which can be used to track progress, compare it to baseline plan and forecast future ones as shown in Figure 16.

5.3 VSM Methodology: Case Study 2

The framework is applied for in an earthmoving pilot project. The project's scope of work comprises the excavation and hauling of unsuitable material and the placement of backfill material. The excavated material needs to be hauled approximately 750 metres to an onsite stockpile, while the backfill material (crushed gravel) needs to be hauled approximately 500 metres from another onsite stockpile. The backfill material needs to be compacted to a 95% standard proctor density.

The project team developed a construction execution plan that has five crews: (1) an excavation crew (EC) that has two dozers, (2) a loading crew (LC) with two excavators, (3) a hauling crew (HC1) for excavated material, consisting of nine articulated trucks, (4) a backfill crew (PC) with two dozers, one water truck, and two compactors, and (5) a hauling crew (HC2) of seven articulated trucks to haul backfill material.

Step 1. Identify Customer Needs

The client requires the project to be completed at the lowest possible cost, on time, and according to the project's design drawings and specifications. Customer's needs can be achieved by hauling

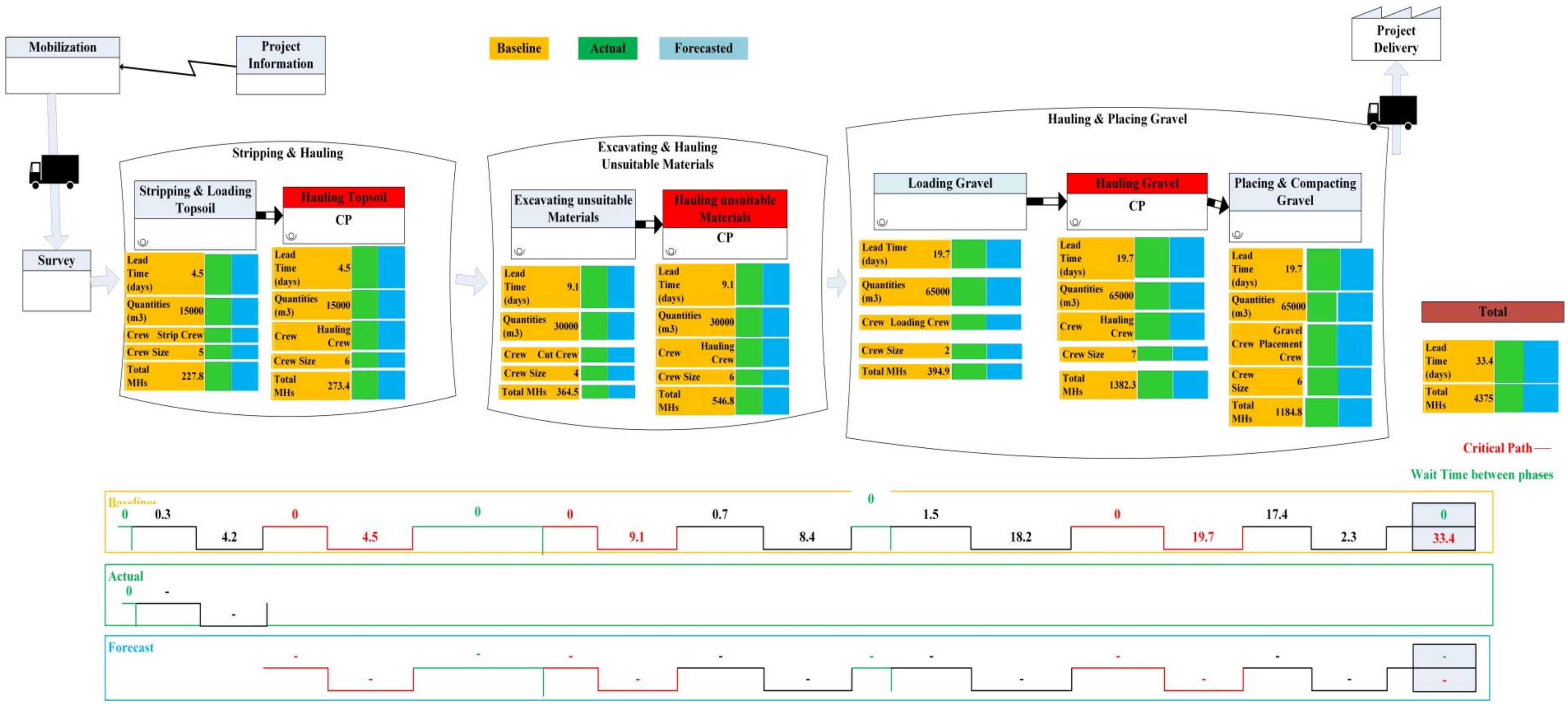

Figure 16: VSM Case Study 1- Plan Vs Actual Vs Forecast VSM

excavated materials and placing the backfill materials as per estimated productivities to maintain baseline project schedule as well as avoid cost overrun. The quality control team will monitor the backfill activities to ensure quality standards are met.

Step 2. Identify the Process

The activities and their sequences are identified by using the project's schedule. The resources (crews, their sizes, and manhours) are determined by using the construction execution plan and discussions with the project team. Excavation and Hauling of unsuitable materials will be completed first by EC, LC and HC1 crews; then the backfill materials will be placed by PC and HC2 crews.

Step 3. Select Process Metrics

The process metrics chosen are the lead times, crew names and sizes, and manhours to monitor the project's schedule and progress, which reflect the client's and contractor's requirements. The lead time show activities' durations which can be summed to determine the overall work duration. On the other hand, crew names and sizes as well as manhours show work execution and provide metrics that can be compared to the original plan and estimate.

VSM also tracks the process and wait times that can be used to identify the *value-added time* (VAT) and *non-value-added time* (NVAT) in the process.

Step 4. Develop Current State VSM

The current VSM is developed as shown in Figure 17. Excavating, loading and hauling of unsuitable material are considered to be p*hase one* of the project; they have to be completed concurrently, and before other tasks, otherwise, the extra movement will be needed for the excavated material, thereby increasing the wastes in the process. If excavated material is not loaded directly, it needs to be stockpiled and loaded later, which is an unnecessary extra movement for the materials. Similarly, loading, hauling, and installation of backfill materials are considered to be *phase two* of the projects. We note that the hauling activity in phase one and loading in phase two is on the project's critical path, which is defined as the set of activities that determines the project's overall lead time, [188]. The total budgeted manhours are 15,494 hours, and the project lead time is 41 days.

Steps 5 &6. Classify Activities to Identify and Eliminate Waste

The current PVSM in Figure 17 shows that the major waste in the process is the various wait times, which total 11,828 hours or 76% of the total manhours. The result is following other studies that show that the waste in the construction industry ranges between 47% and 80%, [189]. The industry has normalized the waste in its processes, so implementing VSM in the construction project planning phase can expose the waste and allow the project team to eliminate it.

NVAT can be classified into two categories: *essential NVAT* that cannot be eliminated due to resource or technology limitations (for example transportation and storage), and waste that can be eliminated, [68]. Critical path activities can facilitate the classification of NVAT, i.e., wait time for a critical path activity is a waste while the wait time for a noncritical path activity is essential NVAT if the resources for this work cannot be utilized by other activities.

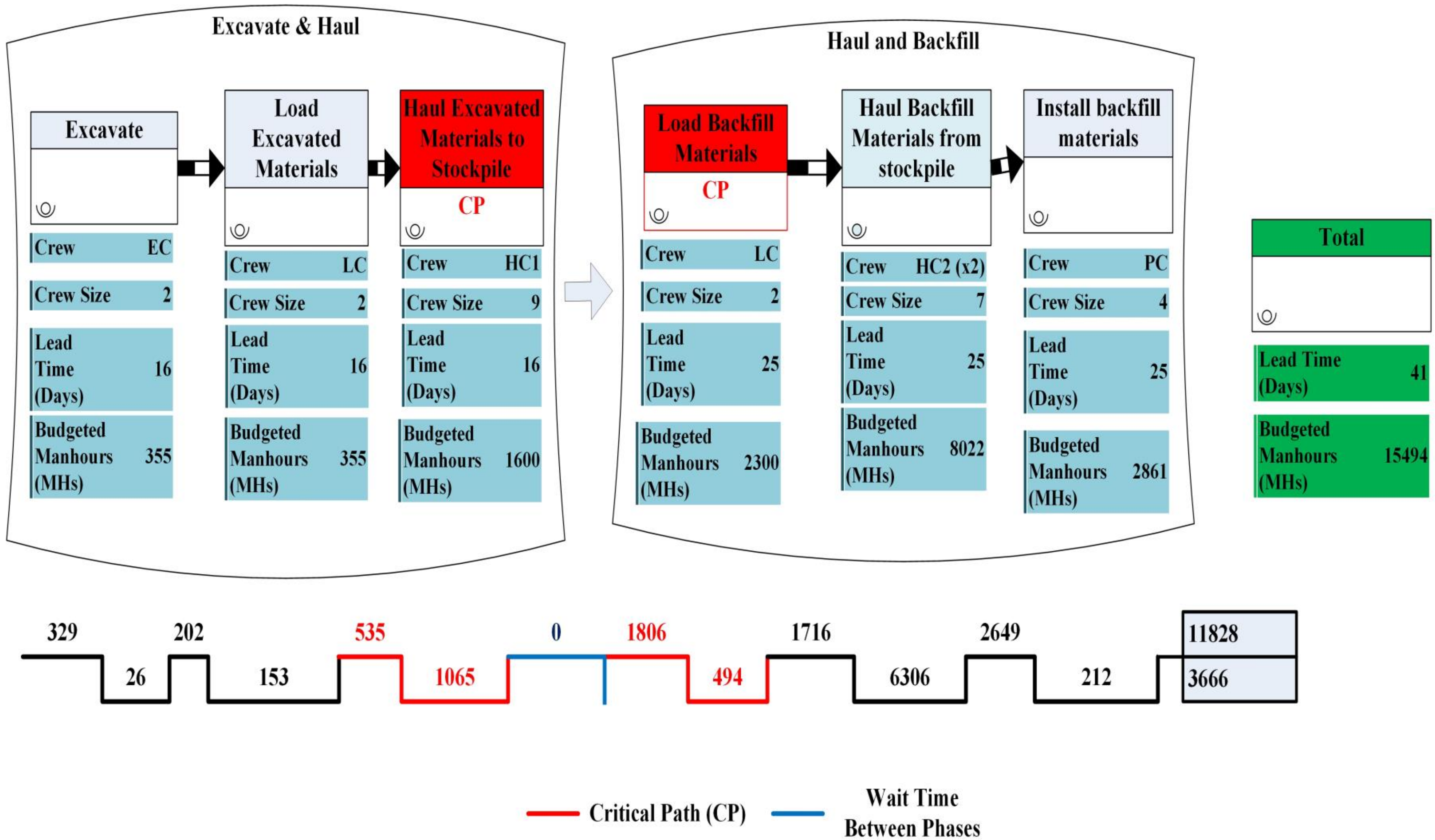

Figure 17: VSM Case Study 2- Current Planned VSM

Step 7. Identify and Remove Constraints to Increase Workflow

The major constraints identified for the project are the ground disturbance permit, which is required to start excavation and the geotechnical testing requirements for the backfill materials. The ground disturbance permit ensures all underground utilities are identified and located by surveyors, so the earthwork activities can be executed safely. On the other hand, the geotechnical testing requires soil analysis for the backfill materials to determine its composition and the criteria to meet the project quality standard by achieving 95% standard proctor density. These constraints can interrupt the workflow as the associated crews cannot commence the work unless these constraints are removed.

Step 8. Create Future "Planned" VSM

Using the classification of activities in Step 5, the future PVSM is developed as shown in Figure 18. The waste time, i.e., waiting time for critical path activities is minimized and the crews' estimated productivity rates are increased by minimizing time and capacity buffers built within them. This reduced the NVAT from 11,828 hours to 1,703 hours (an 86% reduction), and the total budgeted manhours decreased from 15,494 hours to 5,368 hours (a 65% reduction).

Steps 9, 10 &11. Monitor future PVSM, Analyze Completed Activities and Create Forecast Plan

The future PVSM is updated, and process metrics are actualized for completed activities and compared to the baseline plan. This allows the project team to track performance and ensure work is progressing as planned and to revise the plan, if needed, due to any unforeseen site conditions during the planning phase. In our case, once the project team mobilized to the site, a topographical

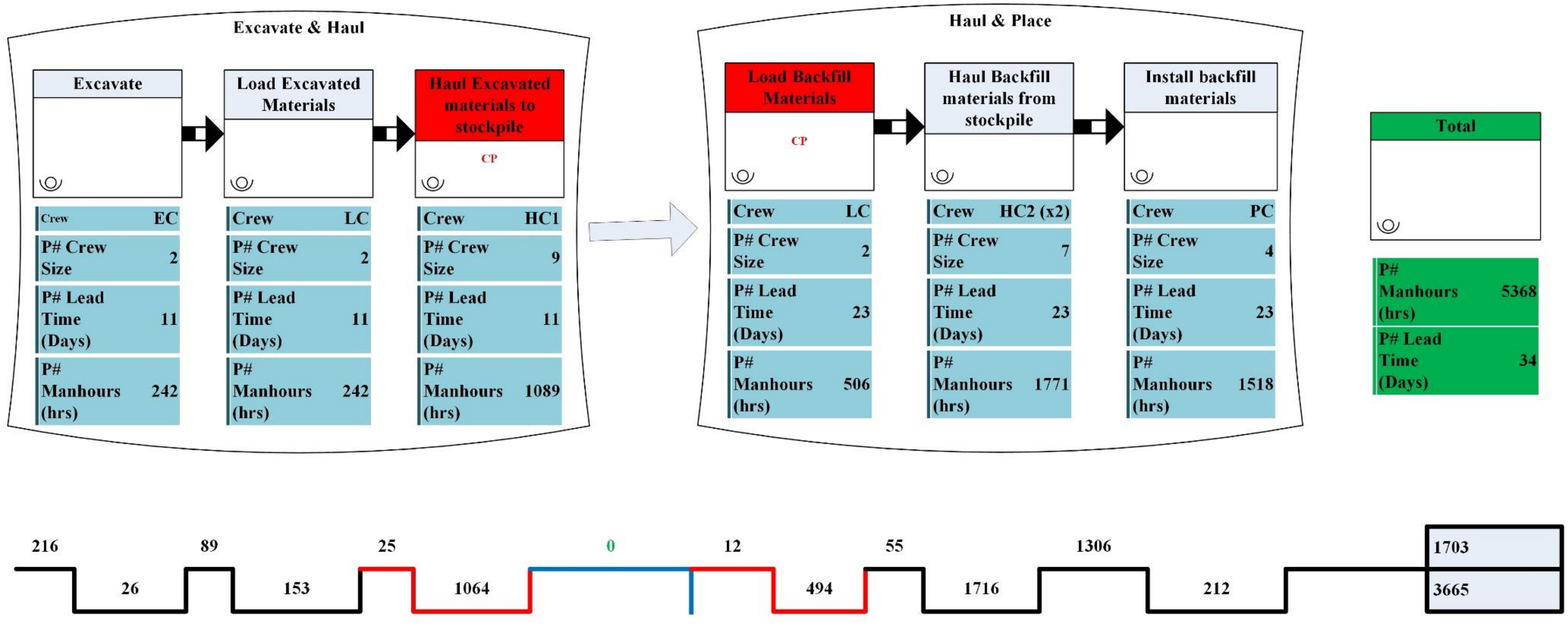

Figure 18: VSM Case Study 2- Future planned VSM

survey was completed which showed that the execution and backfill materials were less than what was presented to the project team during the planning phase. The decrease of material quantities shortened activities lead time and budgeted manhours, as shown in Figure 19. The process metrics for completed activities were tracked and used for forecasting the remaining activities based on the new quantities, also shown in Figure 19.

The actual lead time for *phase one* is 5 days, and the forecasted lead time for *phase two* is 8 days based on the revised quantities. The forecasted project lead time is thirteen days compared to thirty-three days in the original plan. Also, the forecasted manhours are 2,564 hours compared to 5,368 hours in the plan. The updated VSM shows that the actual manhours for Phase One are 716 hours, with 322 facilitates managing the project resources, i.e., planning to utilize crews on other activities if possible, or demobilized from site.

Step 12: Final Plan Vs Actual

The future PVSM is updated for *phase two*, and process metrics for completed activities are actualized, as shown in Figure 20. The actual project lead time is twelve days, with 2,333 manhours, and the NVAT is 669 hours, which is 29% of the total man-hours, a significant reduction from the 76% originally estimated. Moreover, the hauling activity in phase two became a part of the project's critical path, which reduced the overall project lead time as it has the highest man-hours per crew.

The developed VSM framework was applied in our case study, and the summary results are shown in Table 9, below. The results show that the method can be an efficient tool in planning construction activities, eliminating waste, monitoring during the execution phase, and forecasting

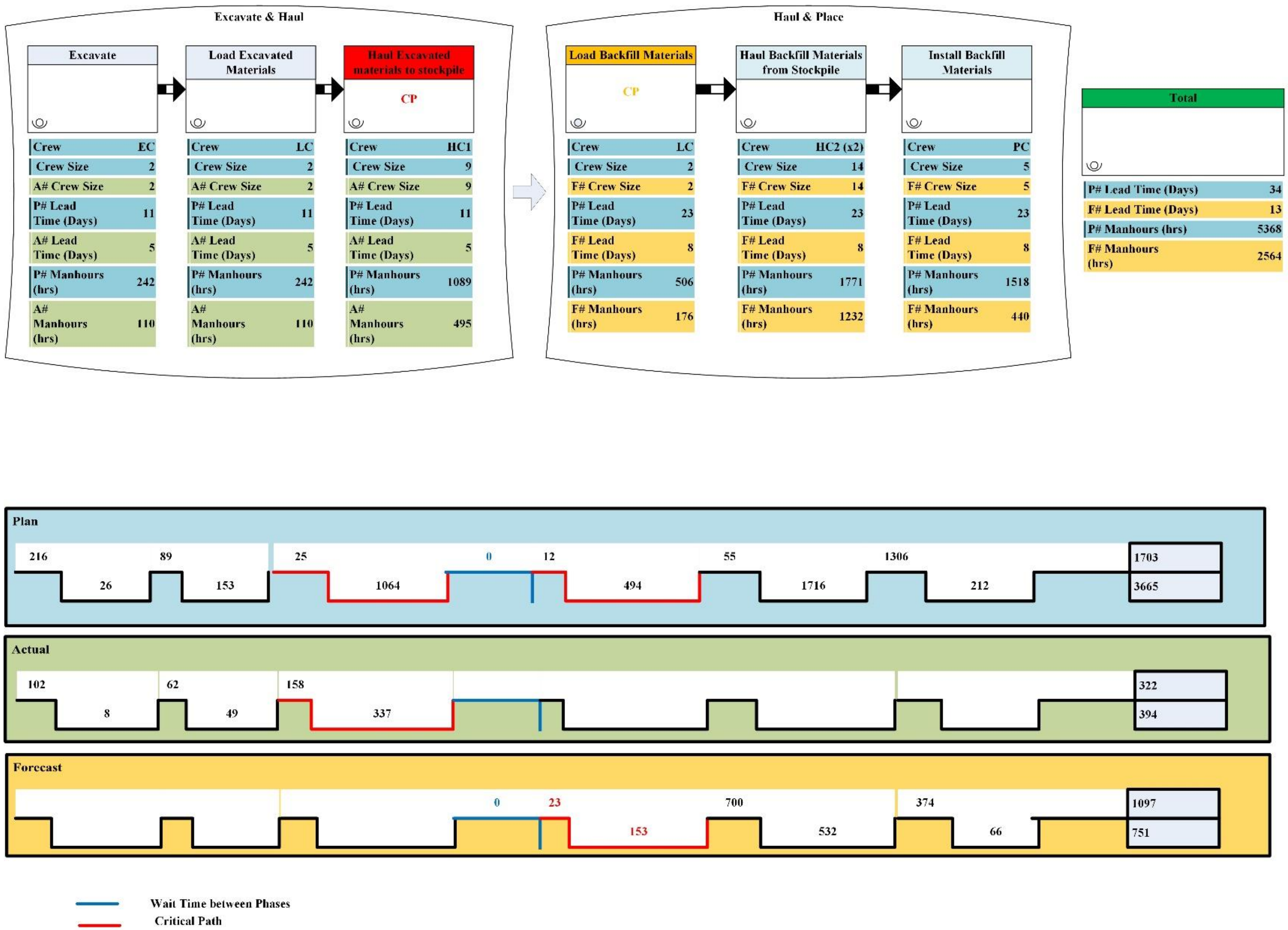

Figure 19: VSM Case Study 2- Plan Vs Actual Vs Forecast VSM

remaining activities. This methodology can be suitable for non-repetitive processes where it identifies and eliminates wastes before execution.

Table 9: Summary of Case Study Results

	Original Plan	PVSM	Actual
Lead Time (days)	41	34	12
Budgeted Manhours (hours)	15494	5368	2333
NVAT (%)	76%	32%	29%

5.4 VSM Methodology: Case Study 3

The developed framework is applied in a concrete placing case study. The project's scope of work comprises supplying materials, equipment and labourers to install two equipment foundations. It includes the supply and install of surveying, void form, concrete steel embeds, anchor bolts, bond breaker, concrete formwork, reinforcing steel, and concrete.

The planning team developed an execution plan that has three crews: (1) carpenters crew (FC) to install formwork, bond breakers and isolation joints, (2) masons and labourers crew (CC) to install concrete and fill-concrete, and finally a crew to install reinforcing steel (RC). The sizes of the crews will vary depending on the activities and workload. The execution plan shows the contractor will scan the site to determine existing underground utilities and mark to avoid damaging them. The scans will be followed by a topo survey to determine existing ground elevations as well as locate the coordinates of the foundations. Formwork, reinforcing steel, and concrete crews will

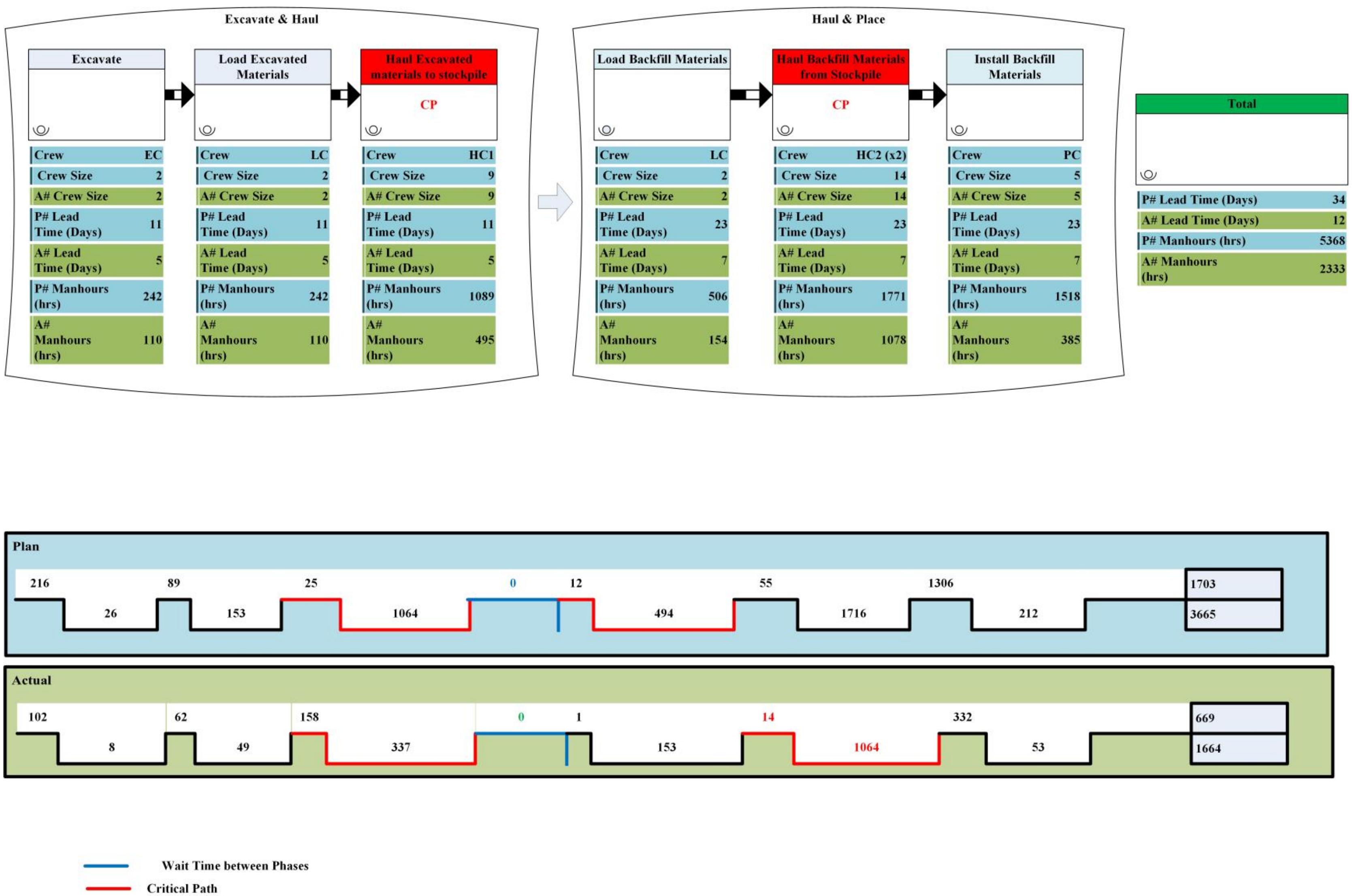

Figure 20: VSM Case Study 2- Final Plan Vs Actual VSM

execute the work. The lead times for foundations 1&2 are 23 and 33 days respectively as shown in Figure 21.

The VSM framework is implemented using the following steps:

Step 1. Identify Customer Needs

The owner requires the project delivered with the lowest possible cost, on schedule, and as per design drawings and specifications. Customer's needs can be achieved by installing concrete foundations as per estimated productivities to maintain baseline project schedule as well as avoid cost overrun. The quality control team will monitor the backfill activities to ensure quality standards are met.

Step 2. Identify the Process

The activities and their sequences are identified using the project's schedule as shown in Figure 21. The resources i.e. equipment, materials and labourers are identified using the construction execution plan.

Step 3. Select Process Metrics

The chosen process metrics are process time, lead time, crew, crew size and activity ratio. These process metrics represent the project execution plan which allows the project team to measure progress and process efficiency. The lead time show activities' durations which can be summed to determine the overall work duration. On the other hand, crew names and sizes as well as manhours show work execution and provide metrics that can be compared to the original plan and estimate.

Step 4. Develop Current VSM

The current state map for the plan is developed using the project estimate, schedule and execution plan. Each foundation has its construction work package, estimate and execution plan.

Based on the productivities and activities estimated manhours, the total wait time for workers is 129.1 and 118.2 hours in foundations 1&2 respectively while the total process time to complete the works are 1830.9 and 1421.8 hours for foundations 1&2 respectively. The activity ratio for the processes to install the two foundations are 93.4% and 92.3%. respectively. The total working days are 23 and 33 days for foundations 1&2 respectively. All activities are on the critical path i.e. they have a finish-start relationship. The current VSM for the plan is shown in Figure 22.

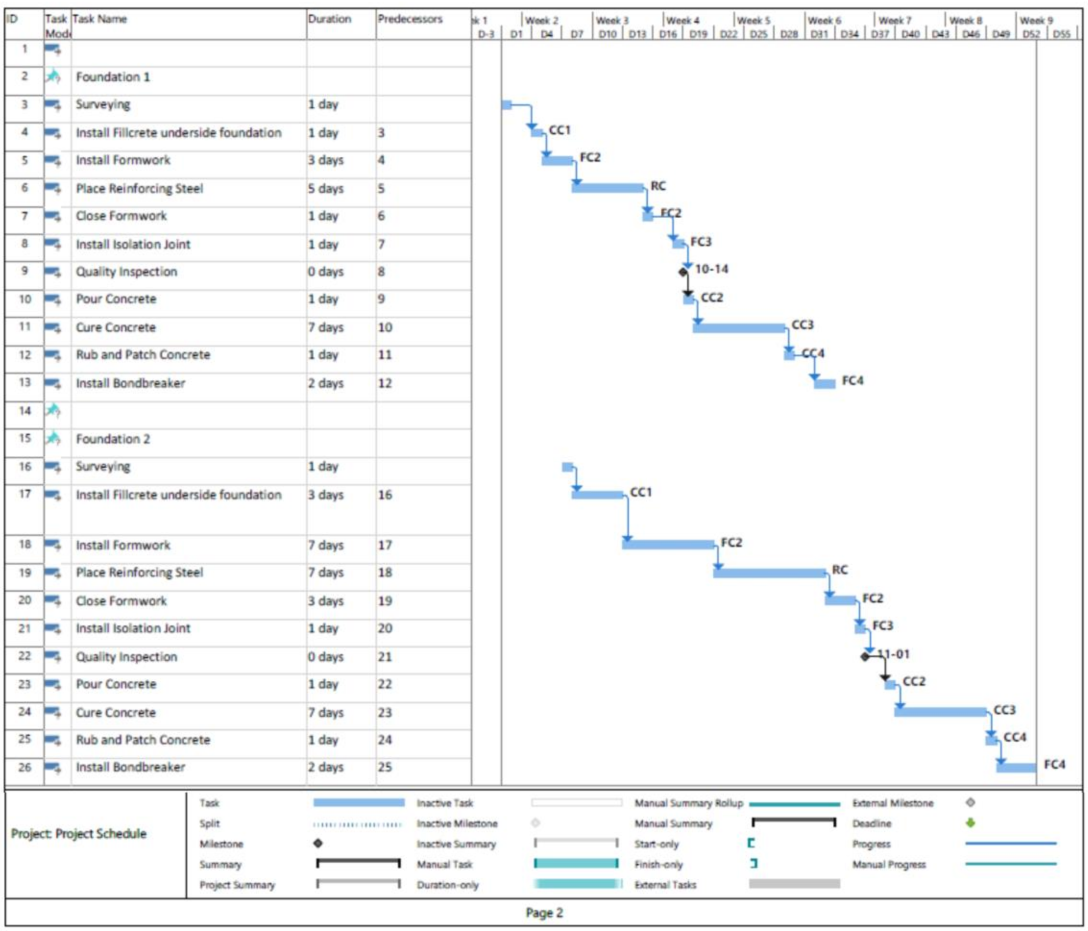

Figure 21: VSM Case Study 3- Project Schedule

Steps 5&6. Classify Activities to identify & Remove Waste

The major waste in the process is the waiting time for the workers. The wastes are 6.5% and 7.7% for foundations 1 & 2 respectively. The two foundations are estimated separately and since the plan is not to execute the work simultaneously, most probably the workers who are performing the work on foundation one will not be the same crews for foundations two as the workers may be transferred to a different site or be hired by a different employer, so worker training costs are

carried in the two budgets. The extra training for new workers is considered waste as it adds no value to the project. The foundations are close to each other, so the set-up time for foundation two is waste as well as the movement of materials, equipment and labour is NVAT that should be minimized.

Step 7. Identify and Remove Constraints to Increase Workflow

The workflow would be improved significantly if the foundations can be installed consecutively i.e. the crews can start working on foundation two after completing foundation one. This will eliminate the extra training required for new workers who may be required to work in foundation two; it also minimizes the extra time required to set up equipment and materials for foundation two as the same set up can be used for both foundations. Furthermore, more work fronts will be available for the workers i.e. workable backlog can reduce the waiting time for the workers and enhance productivity.

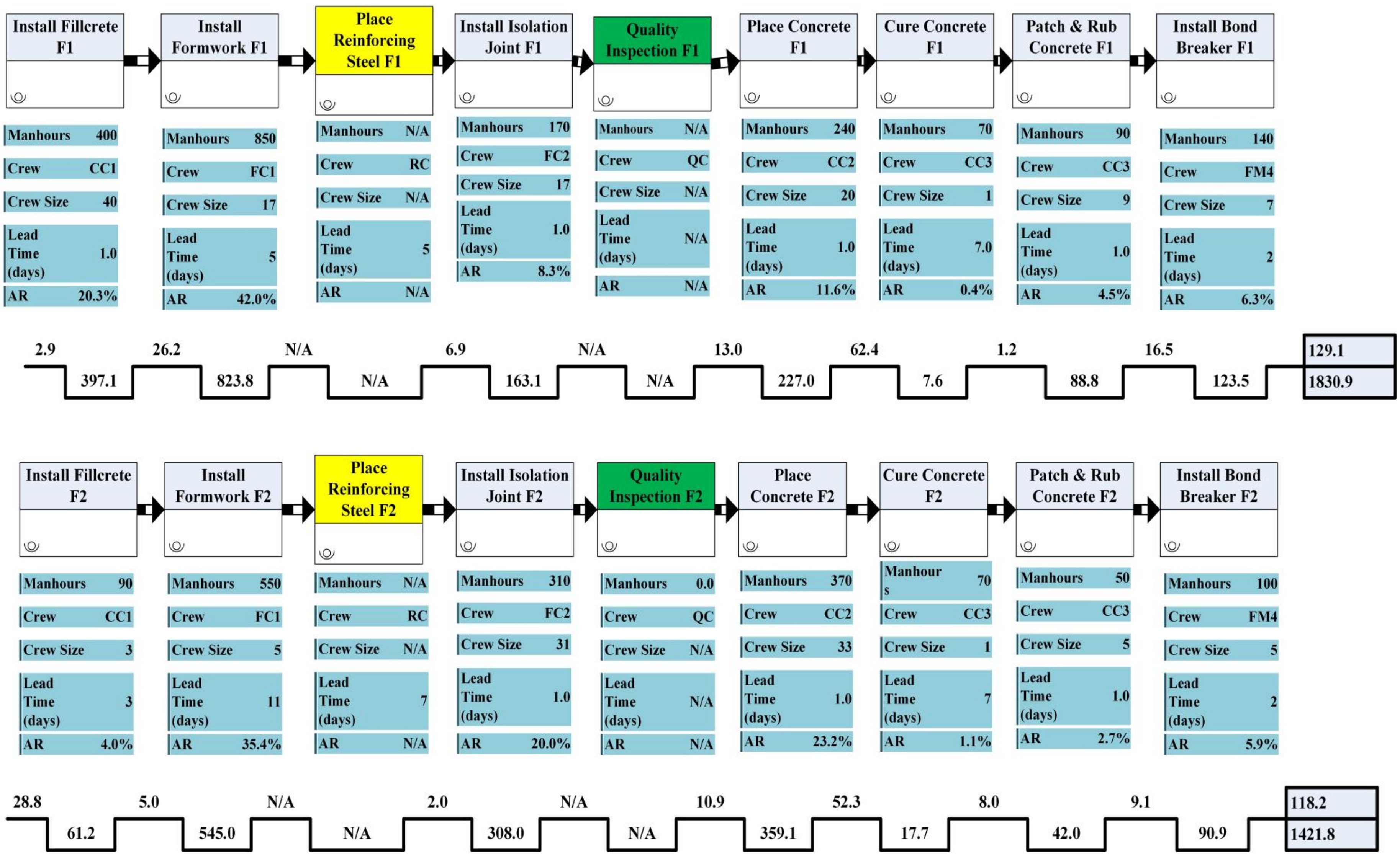

Figure 22: VSM Case Study 3- Current Planned VSM

The contractor can hire more workers to increase the capacity (if needed) so it can meet the deadlines for the two foundations. Also, the two foundations can be poured on the same day as the concrete supplier can supply 400 m3/hour. This also can reduce the equipment costs for placing concrete. The concrete pump will have a better utilization in pouring the two foundations on the same day as well as reduce the mobilization and demobilization costs. Furthermore, the overall project lead time will be improved as the concrete for the two foundations will be cured during the same time after placing it.

Step 8. Create Future "Planned" VSM

The future Planned Value Stream Map (PVSM) is created to eliminate waste and increase workflow as identified in steps 5, 6 and 7. The plan shows the two foundations will be installed consecutively. The processes to install the foundations are identical, so they are combined into one process to facilitate planning and progress tracking. The plan is revised, and the extra time required to train the new workers that were carried in the original budget is eliminated as well as the equipment and labour required for separate concrete crews are eliminated. The gain in efficiency due to creating a workable backlog cannot be quantified but it will be measured once the work is completed. The Future "Plan" is shown in Figure 23.

The combined working days to complete the two foundations are 56 days while the revised plan has 39 working days which is a 30% reduction in the project if the foundations were installed consecutively. Moreover, the NVAT is reduced from 247.3 hours to 157.3 hours which is a 36.3% reduction.

Steps 9, 10, 11 &12. Monitor Future PVSM, Analyze Completed Activities and Create Forecast and Actual Maps

The future PVSM is monitored during the execution phase of the project, and process metrics are actualized for completed activities to compare actual to planned performance as shown in Figures 24 and 25. The actual project working days and process times are reduced by 28.6% and 28.2% respectively compared to the original plan. However, the actual working days are 40 compared to 39 days in the future PVSM.

The NVAT is the original plan is 7.1% and is reduced to 4.6%, as shown in Figure 26, and the activity ratio in the original plan is 95.2% and 95.8% in the future PVSM and actual one respectively as shown in Figure 27.

The results show that the work was executed more efficiently than the average estimated productivities. For estimating future similar projects, we recommend using this project actual productivities which supports the concept of "lowering the river" i.e. reducing buffers, [189]. This allows the project team to track performance and ensure work is progressing as per plan.

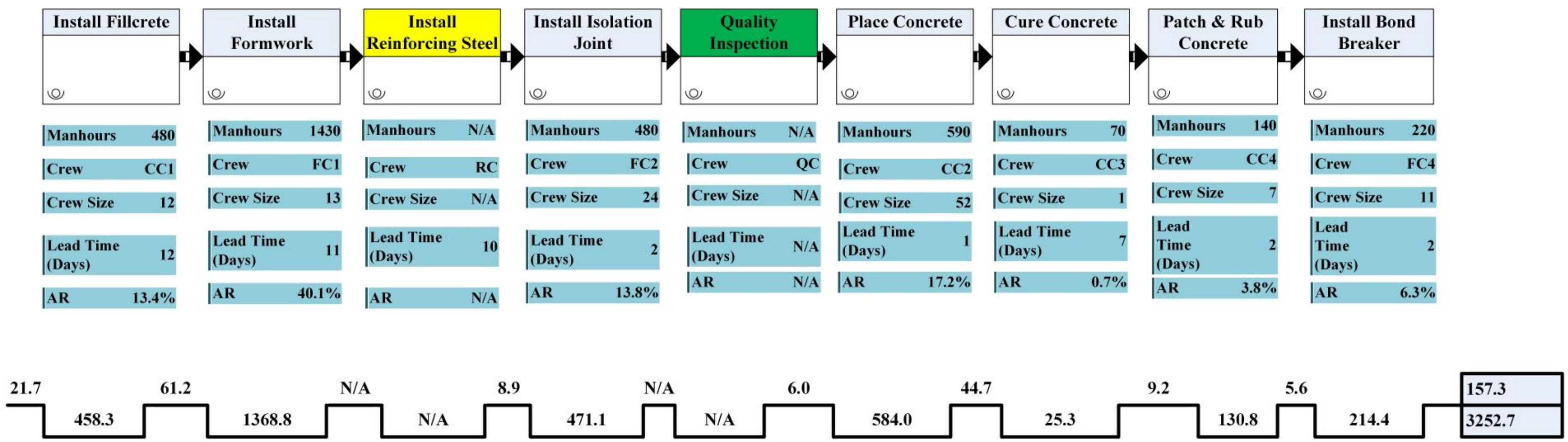

Figure 23: VSM Framework- Current PVSM

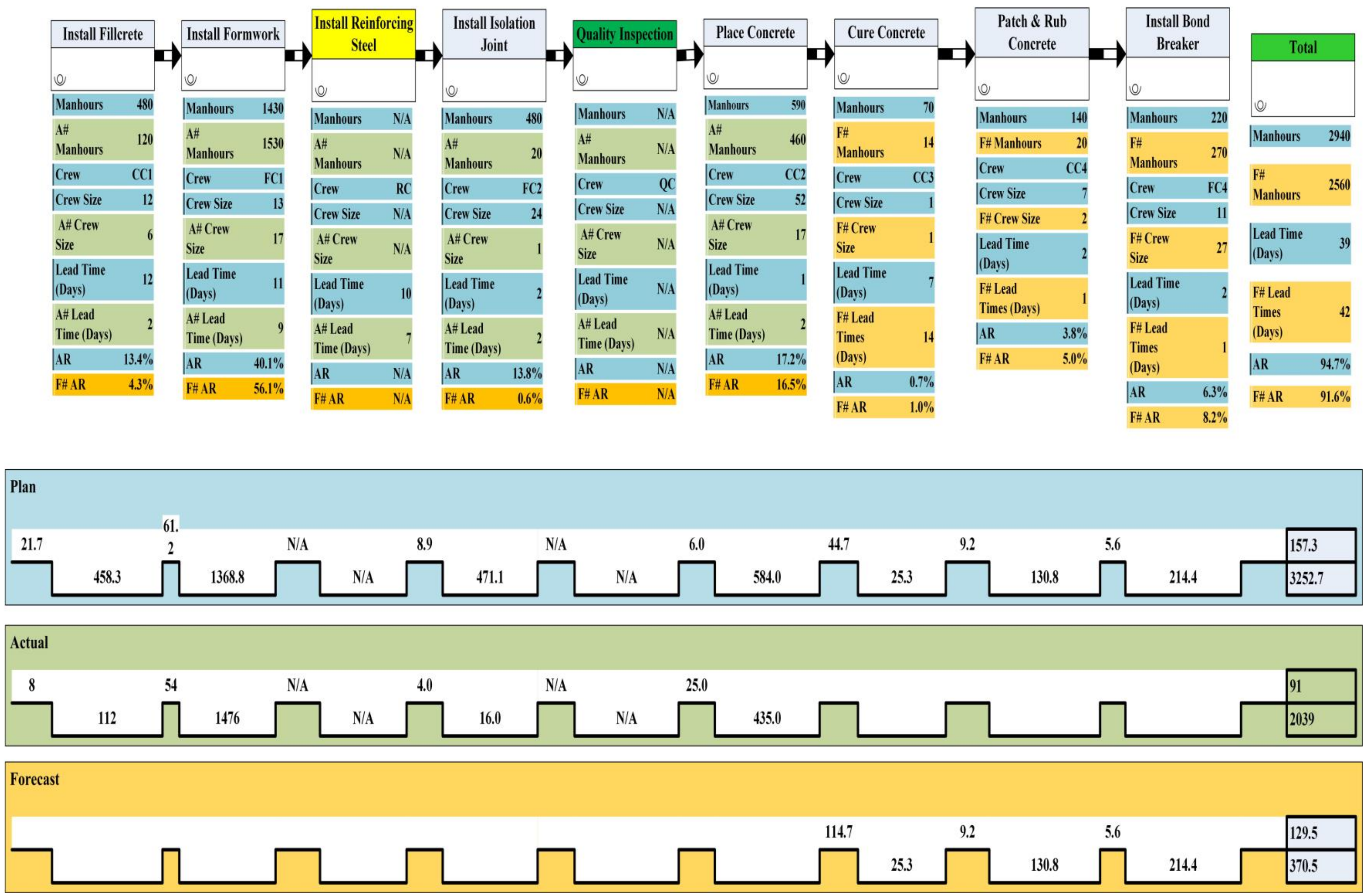

Figure 24: VSM Case Study 3- Monitoring PVSM

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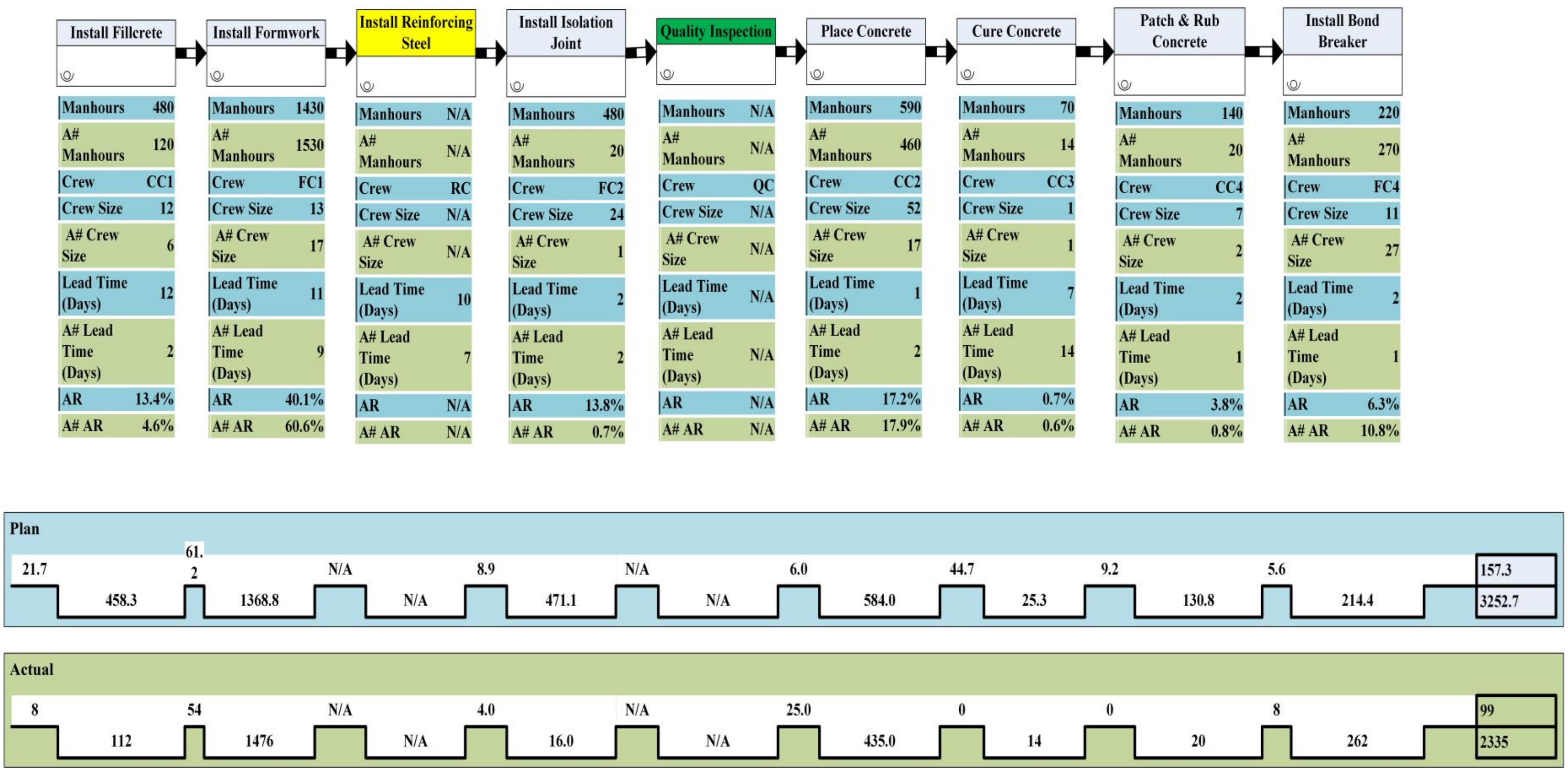


Figure 25: VSM Case Study 3- Plan Vs Actual

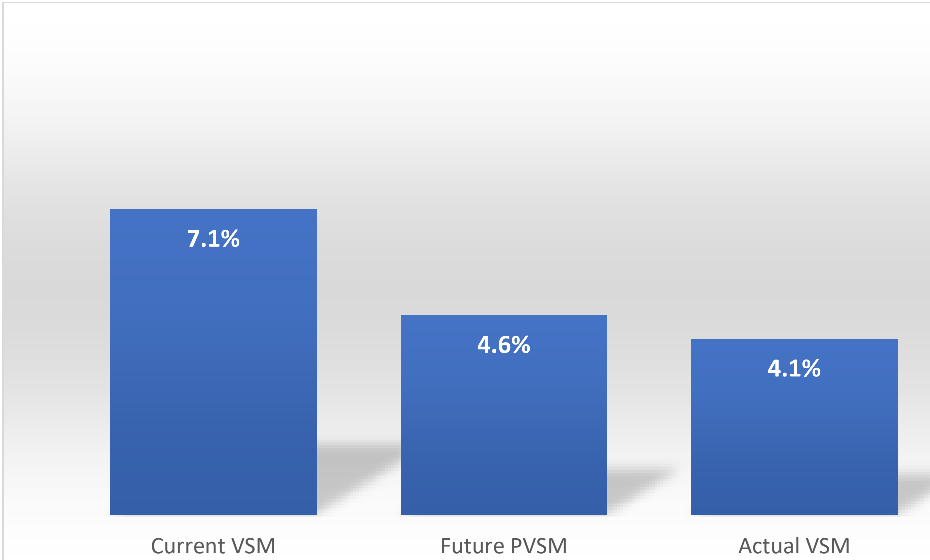


Figure 26: Case Study 3 Current NVAT Vs Future PVSM Vs Actual

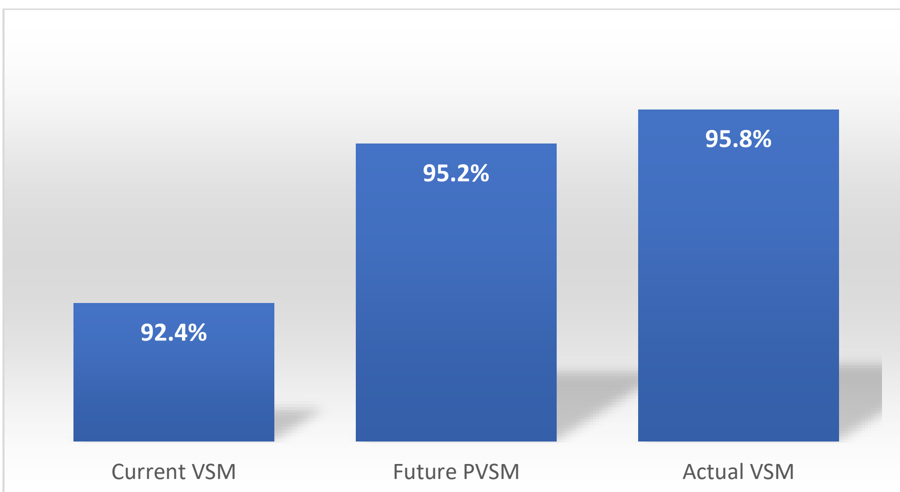


Figure 27: Case Study 3- Current AR Vs Future PVSM Vs Actual

5.5 Case Studies - Conclusion

The developed VSM framework is implemented in three case studies. The results show the framework can enhance the construction execution plan by identifying and eliminating the waste before the execution phase which can ultimately reduce the project's cost and lead time. The framework can enhance the industry's performance in terms of the cost, schedule and lead time at the field level. Moreover, the framework can be used as a project management tool to plan, monitor and control the processes as well as with other lean management tools such as the Last Planner System (LPS) where the VSM framework can be implemented during the planning phase of the project to eliminate wastes and then use it to monitor progress in the field. It's a visual tool that can support the communication and socialization of the execution plan among project partners which supports the collaborative project delivery approaches. However, to facilitate the framework implementation by various project partners, the methodology for applying it should be standardized.

5.6 Ontology To represent VSM Framework

. The ontology approach is adopted in this study to structure and the VSM framework to facilitate its application across enterprises as well as support its automation in the future. Making use of existing ontologies, when possible, is the general principle for building ontologies. The study utilized the BFO structure to develop the VSM ontology which supports interoperability and data integration with other domain ontologies. The framework for building and utilizing existing ontologies developed in manufacturing and design is followed, [137]. The roadmap for developing the model is summarized in the following steps:

- Specify the purpose and scope of the ontology
- Categorize concepts and develop class hierarchy
- Find old similar ontologies
- Reuse existing ontologies
- Identify relations

- Design instances in the ontology

The principal criteria of top ontology are followed by applying the BFO structure. Protégé is used to build the ontology. Protégé is an open-source ontology editor and framework developed at Stanford University. Ontology is represented using VOWL

5.6.1 VSM Ontology Model

The entities for the VSM model are arranged based on the Basic Formal Ontology (BFO) structure. The model is based on four major entities which are customer requirements, processes, output (VSM) and resources as shown in Figure 28. The customer needs and/or requirements initiates the VSM process that uses resources and results in current and future VSMs.

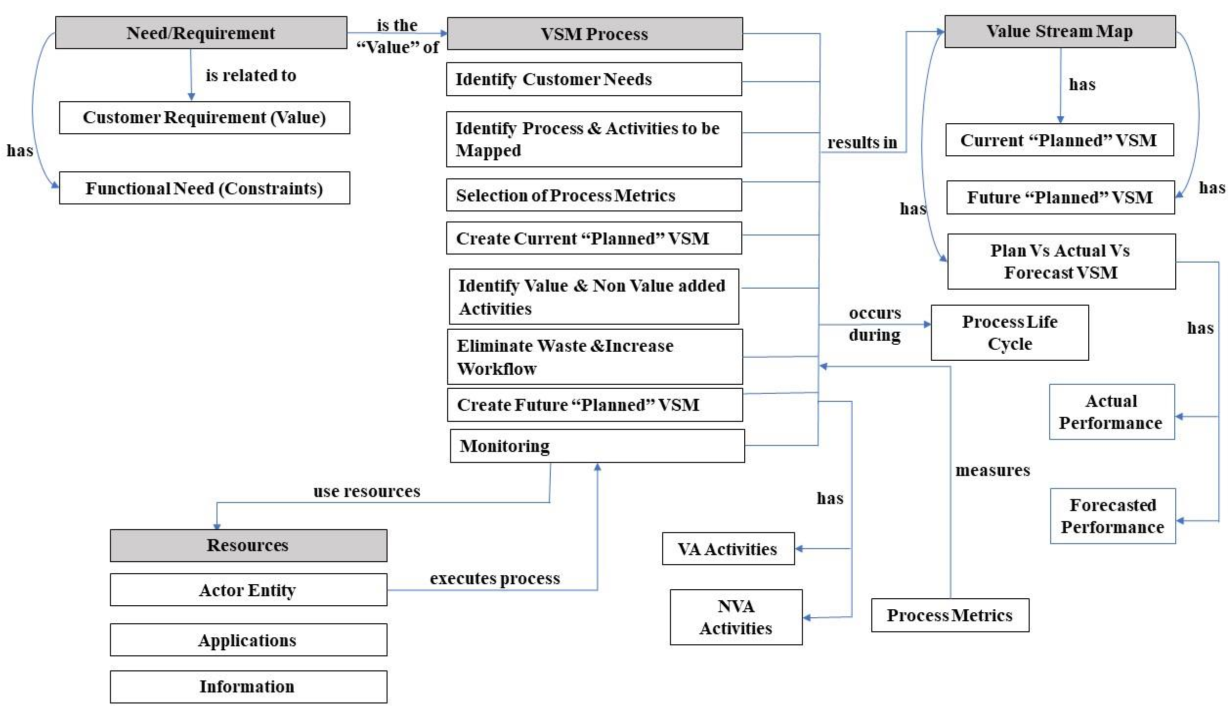


Figure 28: VSM ontology Model

Following are the steps followed in developing the ontology:

Step 1: *Specify the purpose and scope of the ontology*

The scope of the ontology is establishing a common understanding of the VSM framework by structuring its knowledge to facilitate its application along with construction supply networks.

Step 2: *Categorize concepts and develop a class hierarchy*

BFO describes concepts in terms of continuants and occurrents. Continuants are entities that exist through time while occurrent are events or processes in which continuants participate, [190]. Continuants have three major subclasses, [113]:

(i) Independent continuants which represent entities that can exist by themselves such as objects. Material and immaterial entities are the two major subclasses for the independent continuants. In VSM ontology, physical resources such as actors, materials, equipment, etc. are represented as a subclass of the material entity while non-physical resources such as software, applications are represented as a subclass of the immaterial entity.

(ii) Specifically dependent continuant which represents entities that depend on other entities to exist such as colour, mass, etc. In VSM ontology, process and activities qualities such as process metrics and wastes are represented as subclasses of specifically dependent continuant. These qualities measure and describe activities and processes, and their existence is dependent on the existence of associated activity or process.

Generically dependent continuant (GDC) which are entities that cannot exist unless other entities exist and can migrate from bearer to another such as pdf file. In VSM ontology, information is represented as a subclass for the GDC. Information needs a bearer to exist, and they can migrate from bearer to another.

(iii) The second major entity for BFO is the occurrent which has two major entities, [120]:

(1) Processes which are entities that exist in time by occurring or happening.

In VSM ontology, activities and steps to develop current and future VSMs are represented as subclasses of processes.

(2) Temporal region which are entities that are part of the time. In VSM ontology, the timeframe for all entities are represented as a subclass for the temporal region.

(3) Generically dependent occurrents are represented in VSM ontology as changes or events that occur and depend on the existence of other occurrences such as cost reduction, quality improvements, requirement and function entities.

The concepts for the VSM ontology are shown in Appendix B.

Step 3: *find old similar ontologies*

This study represents one of the first attempts to develop an ontology for VSM.

Step 4*: Reuse existing ontologies*

Existing ontologies should be examined and should be used instead of developing new ones to support the interoperability of ontologies. In this study, we used the BFO structure to structure the VSM framework.

Step 5: *Identify relations*

The representation of concepts in ontologies involves the representation of their relations which defines how the entities are connected. There are three major relations: (1) universal-universal relation which represents “is_a” i.e. is a subtype of; (2) Universal-Particular relation which represents instantiates relation e.g. John instantiates human being; (3) particular- particular relation such as part of relation e.g. john’s arm is part of John, [116]. In VSM, major relations and object properties are developed to describe the relationship among entities as shown in Table 10.

Table 10: Lists of object properties summary of the VSM ontology

Relation	Domain	Range
hasFeatures	VSM System	VSM_Features
usesNonPhysicalResources	Process	Non_Physical_Resources
locatedInSaptialRegion	Material Entity	Spatial_Region
executesProcess	Actor	Process
hasProductComponent	VSM Service System	Product_Component
hasSoftwareFeatures	VSM Service System	Software_Features
usesPhysicalResources	Process	Physical_Resources
hasPCQualityStatus	Product Component	Quality_Status
hasSSQualityStatus	VSM Service System	Quality_Status
hasPRQuality	Physical Resources	Quality_Status
hasNPRQuality	Non-Physical Resources	Quality_Status
mentionsAboutStakeholderRelation	Contractual Requirement	Stakeholders_Relation
identifiesProcessMetrics	Selection of Process Metrics	ProcessMetrics
identifiesActivityType	Activities Classification Process	Activity_Type
IsRelatedToCustomersNeed	Identify Customer Needs	Customers_Need_Entity
resultsInCurrentVSM	Creation Current VSM	Current_VSM
resultsInFutureVSM	Creation of Future VSM	Future_VSM
hasFunctionalNeed	VSM Process	Functional Need Entity
occursDuringProcessLifeCycle	Process	Process_Life_Cycle
occursAtMilestone	Process	Milestone

Step 6: Design instances in the ontology

instances are developed for the ontology to provide guild lines for future users to develop their own. For example, Visio Software is an instance for VSM software; Enterprise Resources Planning (ERP) is an instance for Information Technology in-process metrics. VOWL is used to represent the ontology as shown in Figure 29, [191]. VOWL is a well-specified visual language for ontology representation, [192]. VOWL representation shows the classes of the ontology and their subclasses.

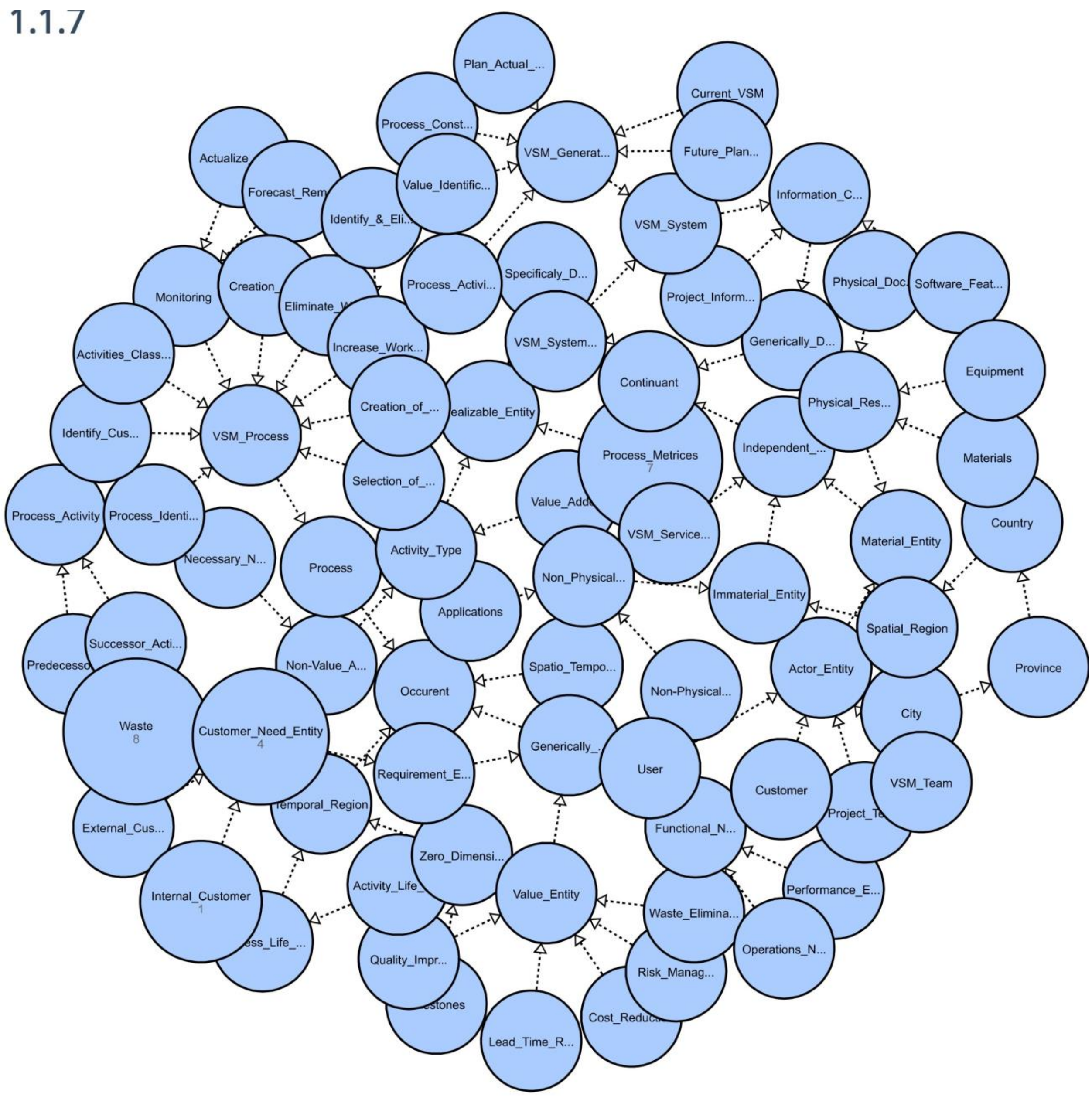


Figure 29: VOWL VSM Ontology

5.6.2 VSM Ontology Evaluation

Ontology evaluation is described in two terms: validation and verification. VVerificationdeals with building the ontology correctly, while validations refers to whether the ontology represents reality or not, [193].

HermiT, a protégé built reasoner, is used to verify the consistency of the ontology as well as the relationship between classes and subclasses. The ontology is processed in 3349 ms using Hermit 1.3.8.413. Oops is another ontology validation tool that is also used to validate it.

5.6.2 VSM Ontology Conclusion

Construction processes require information and material flow across enterprises. Moreover, CSC has multiple levels and a large number of partners which may hinder the implementation of VSM along construction supply chain networks. Therefore, *multilevel* VSM can be a key to map construction processes due to the large number of partners in the construction supply chain (CSC). However, mapping processes across enterprises requires standardization for the VSM methodology. The developed ontology can form a step towards a standardized VSM methodology for the construction industry. VSM ontology can also support streamlining VSM processes and *d*ata integration among project partners which can promote the multilevel VSM concept. The study attempts to develop one of the representations for VSM ontologies in the construction industry which can facilitate its application by structuring and establishing a common understanding for it. VSM ontology was developed using BFO as an upper ontology to facilitate interoperability and data integration with other domain ontologies. VOWL is used to represent the ontology. In the future, this ontology model will be extended to construction project management.

Chapter 6: Ontology Model to Structure Construction knowledge

The ontology concepts, object properties, and instances were developed through an iterative process, using ISO 12006-2 recommendations and by conducting interviews with domain experts who have intensive experience in the industry as shown in section (2) of Figure 30. The BFO structure was reviewed with the experts; then the classes and their relationships of the developed ontology were established based on their inputs. They provided the ontology classes, properties and their relations. ISO 12006-2 is an international standard that provides a basis for classifying construction systems. It also gives examples that explain the construction concepts, so organizations can develop their classification systems. Following ISO 12006-2 recommendations can facilitate adapting and standardizing the framework in the industry.

We used Protégé to build the ontology and WebVOWL to represent it as shown in section (3) of Figure 30. Protégé is an open-source ontology editor and framework developed at Stanford University. WebVOWL is an ontology visualization tool that aims to provide an intuitive and comprehensive representation that can be understood by users less familiar with ontologies, [192]. The ontology is evaluated by using Protégé's built-in reasoner that validate the consistency of the ontology as well as the relationship between classes and competency questions answered by industry experts.

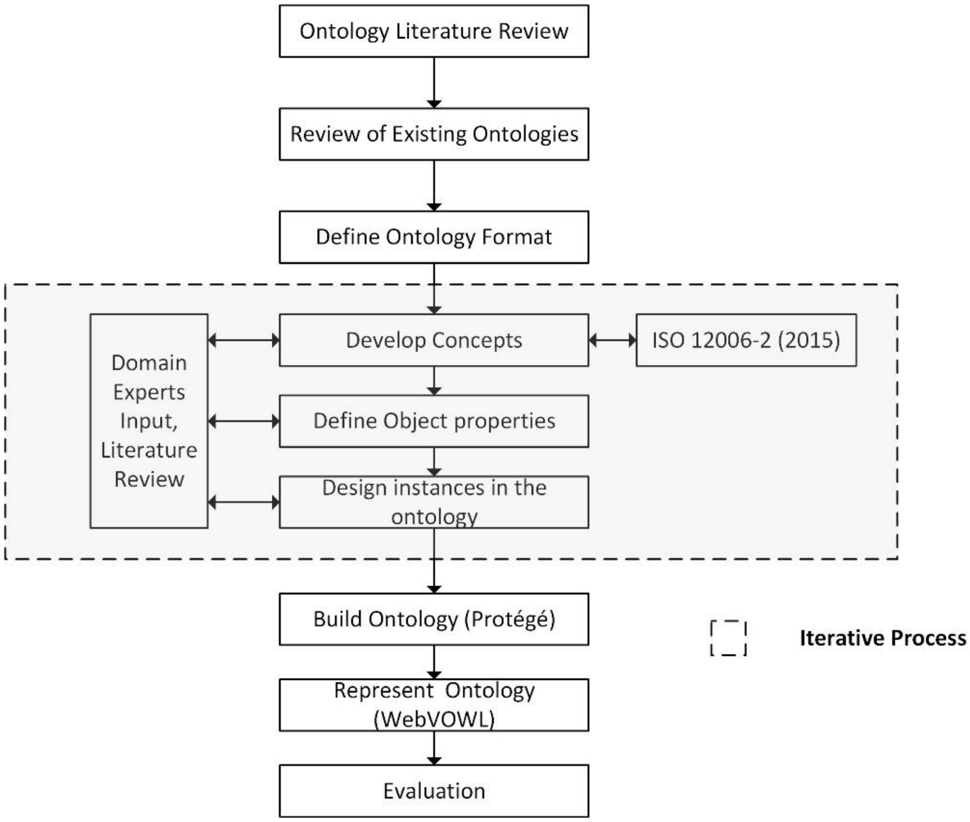


Figure 30: Construction Knowledge Ontology Developing methodology

The scope of the ontology is to structure construction knowledge from the project's early phases through to completion to streamline information flow and support data integration with other domains. A summary of the ontology framework is shown in Figure 31. The origin of a construction project is the need to build a construction entity to fulfil a requirement such as living, producing, or manufacturing. The project should meet certain criteria such as financial, jurisdictional, social, and engineering that may act as guidelines and constraints for the project. The needs and requirements to build the entity initiate the processes, which include but are not limited to pre-design, design, construction execution, operations, and disposal, as shown in Figure 31. The processes occur during a process life cycle which is the timeframe for the process and/or activity; the process uses resources such as construction aids, e.g., scaffolding and earth moving equipment, which is equipment and/or materials that support the processes, but they do not form a part of the construction entity. Actors such as engineers and construction professionals execute the processes that result in a construction entity that fulfills the owner's needs and requirements. The construction entity, e.g., a building, plant, and bridge, has products such as materials and equipment that form a part of it. It also has spaces and elements, which are a group of materials and/or equipment that form a system such as a wall or HVAC systems.

Formal and upper ontologies facilitate communication among domain ontologies, which supports the interoperability and integration of these ontologies. Therefore, following the BFO structure supports the integration of the developed ontology with other domain ones. ISO 12006-2 (2015) recommendations are followed, which promotes the standardization of the concepts.

Six interviews with domain experts were conducted to have their inputs in developing the ontology. The interviewees have worked for various organizations, and their current positions are General Manager, Construction Manager, Safety Director, General Superintendent, Senior Project Coordinator, and Project Coordinator. They were recruited via the researchers' industry relationships as well as referrals. The BFO was presented to the interviewees, so they understood the structure and the purpose of the ontology. Then the interviewees were asked to develop the classes and their relationships based on their experiences as well as asked to review the partially developed ontology and provide recommendations, so the developed ontology reflects the industry's knowledge.

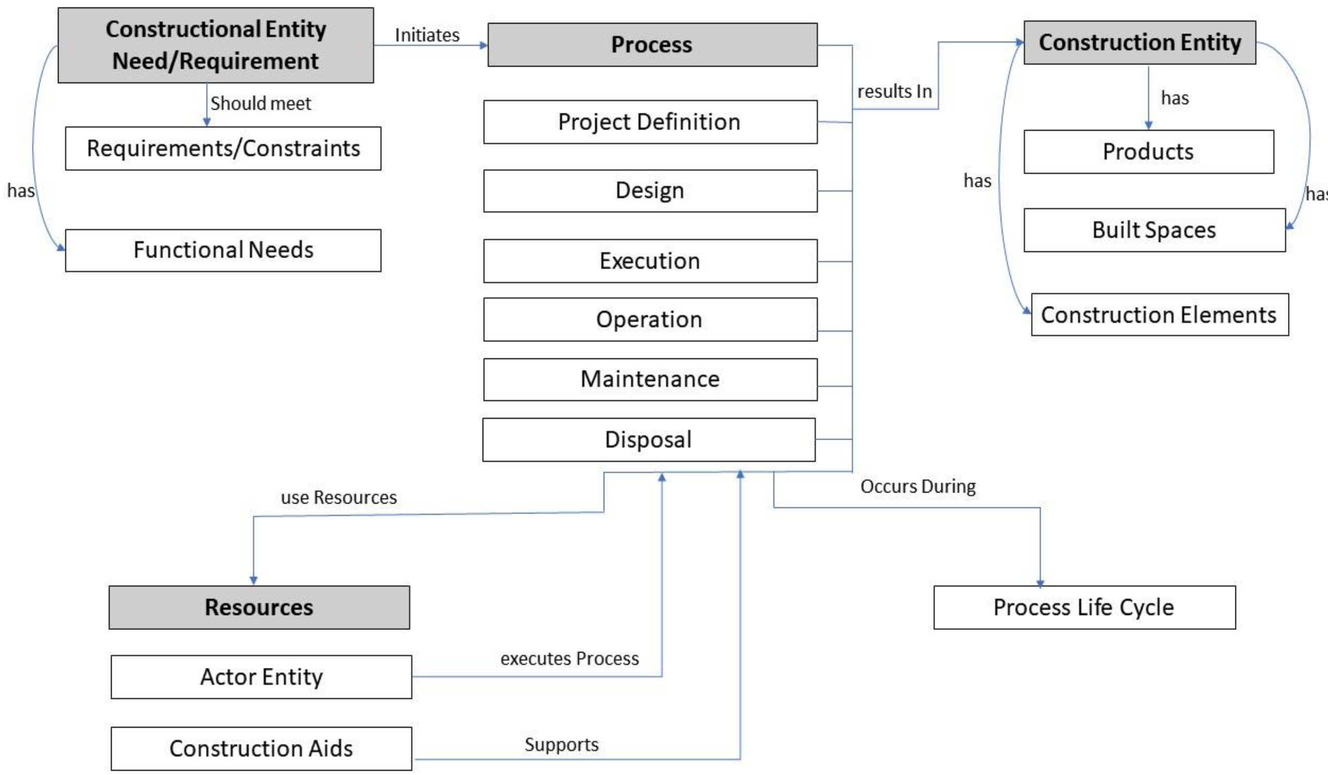


Figure 31: Construction Knowledge Ontology Framework

6.1 Ontology Development

BFO is based on fundamental distinct between *continuants* and *occurrences*. Continuants are entities that exist through time while occurrences are events or processes in which continuants participate, [190].

Continuants have three major subclasses, [113]:

(i) *Independent continuants* represent entities that can exist by themselves, such as objects. Material and immaterial entities are the two significant subclasses for the independent continuants:

- *Material entities* are independent continuants that have three dimensions and continue through an interval of time. In the developed ontology, the material entity has three significant subclasses. The first one is *construction entities*, which result from the execution process such as buildings, plants, facilities. Buildings, industrial and infrastructure entities are the subclasses of construction entities that represent construction sectors. The second subclass of material entity is the *construction resources*, which represent materials, equipment, tools and actors that participate in processes. The third subclass is the *object aggregate*, which is a group of products that form a system. *Construction element entities* such as walls and HVAC systems are the major subclasses for the aggregate object entity.

- *Immaterial entities* are independent continuants that have no material entities as parts. *Continuant flat boundary* and *spatial region* are the main subclasses for the immaterial entity. Continuant flat boundary represents the boundaries and zones for material entities where the processes take place, which can change as materials move. However, the spatial region is fixed and represents the location of entities such as countries and cities. Software is another subclass for the immaterial entity.

(ii) *Specifically dependent continuant* (SDC) entities depend on other entities to exist. *Examples* include colour and mass. SDC has two main subclasses:

- A *quality* describes the internal and external properties for independent continuants, such as mass and colour, respectively. The *quality status* is a subclass for the quality entity and represents the conformance of material entities with design and standards. *Relational quality* is another subclass for the quality entity and describes the relationship among entities that may vary based on projects, e.g., a contractual relationship.

- *Realizable entities* describe the functions and roles of independent continuants that are realized through associated processes such as the function of a construction entity, can be for storing materials (e.g. warehouses) or for living (e.g. houses), etc.

(iii) *Generically dependent continuant* (GDC) entities cannot exist unless another entity exists and can migrate from one bearer to another. And example is a pdf file that needs a place to be stored in (i.e., cannot exist by itself) but can be transferred to other places, such as hard drives. In the construction ontology, information is represented as a subclass of GDC. The information entity has subclasses that represent general industry information such as standards, codes, and project-specific information that result from the project's processes.

The second major class of entity for BFO is occurrences, which have four major entities, [120]:

- *Processes* are entities that exist in time. The processes for a construction project are classified based on the project phases. Processes have sub-processes that can be broken into activities:
- *Project definition* includes all activities and processes that occur before the design phase, such as project shaping and business case development. Project sanction usually takes place at the end of this process.
- *Design process* includes engineering and architectural processes and results in design drawings and specifications that are issued for construction.
- *Execution* includes procurement, installation, and commissioning processes, which result in a construction entity.

- *Operation* is the use phase of the construction entity, e.g., using it for living in a building project or production in a manufacturing facility.
- *Maintenance* is the process that ensures the construction facility is operating as per the design and within acceptable limits.
- *Decommissioning* is the process that shuts down the construction entity from operational status.
- *Disposal* is the process of removing the construction entity and then reinstating the zone as required.
- *Process boundaries* depend on the existence of the process. They form the boundaries that the process should operate within, such as customer requirements, functional needs, and legislation requirements.
- *Spatiotemporal region* is a part of spacetime, e.g. the spacetime for a process that has a beginning, an end, and a duration.
- The *temporal region* represents the timeframe for a process. The temporal region has zero- and one-dimensional temporal regions as subclasses. The *zero-dimensional* temporal region represents an instant in time, such as a start or an end of a process or activity, while the *one-dimensional* temporal regional represents an interval of time in which a process occurs. The life cycles for processes are represented as subclasses of the zero-dimensional region.

The WebVOWL is a graphical representation of the developed ontology. It shows the classes and their subclasses, which facilitates the understanding of the ontology, [191]. This visual representation can be very useful for users who are less familiar with ontologies as they can follow the structure of the, its concept and their relationships through an interactive tool, [194]. The ontology classes and subclasses are represented using WebVOWL, refer to Appendix C.

6.1 Design Instances in the Ontology

Instances are the atomic or ground level of the ontology, and they provide specific individuals for the concepts. For example, John is an instance of a Civil Engineer class. Ontology may have only classes and no instances, [195]. Instances are created for the developed ontology to provide examples that can facilitate understanding the ontology and further detailing in the future. For example, BIM is an instant of a modelling software entity.

6.2 Construction Ontology Evaluation

Ontology evaluation is described in two terms: validation and verification. Validation refers to whether the ontology represents reality or not, while verification deals with building the ontology right, [193]. Verification ensures models are built correctly. Static and dynamic tests are common verifications techniques. Static tests are mainly concerned with verifying the model via walkthroughs and examining its structure. However, dynamic test ensures the model is working properly through various techniques such as input-output relation tests and internal consistency checks, [196]. Protégé is used to build the ontology. HermiT, a Protégé built reasoner, is used to verify the consistency of the ontology as well as the relationship between classes and subclasses. The ontology is processed in 3.349 seconds using Hermit 1.3.8.413. Various validation techniques can be used to test models, such as degenerate tests, events and face validity tests. In face validity tests, experts who are knowledgeable about the system are asked if it is reasonable or not, [196]. The aim of the developed ontology is to represent construction knowledge. Face validity is chosen because it can test if the ontology represents reality or not through industry experts evaluation. The ontology is validated against its scope via interviews with experts. The interviewees have worked for various organizations and their current positions are General Manager, Project Manager, Site Manager, Safety Director, General Superintendent, Senior Project Coordinator, and Project Coordinator. Few of the interviewees participated in developing the ontology, and they were asked to evaluate it after many iterations that resulted in the final one. The interviewees are asked competency questions, shown in Figure 32, to evaluate the ontology based on its aim, i.e., representing construction knowledge throughout various project phases and the ability of the industry to use it to structure the domain knowledge, and further detail it. The participants are asked to rate their comments on a 5-point scale where one represents strongly disagree, and five strongly agree. The average answers if the ontology represents the architectural, engineering and construction knowledge and if it is easy to understand and follow is 4.8 and 4.7, respectively. However, the average answers for the ability to apply the ontology at work and use it to structure knowledge and data is 4.6, as shown in Figure 32. The participants strongly agree that the developed ontology is competent according to its scope. However, a more significant participant's sample is required to have more accurate results.

SPARQL querry is completed within protégé and shown in Appendix C. The study focuses on developing the ontology in terms of its concepts and properties and not on the building of a user interface where information can be input into its knowledge base. This will be a future work once the ontology is fully developed

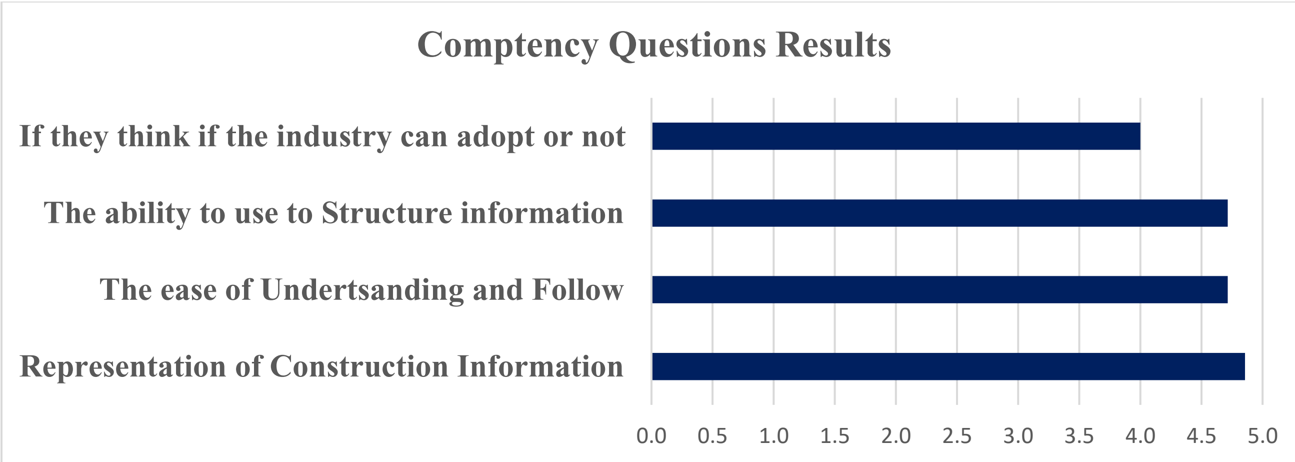


Figure 32: Construction Ontology Evaluation

The developed ontology provides a framework to structure construction knowledge throughout the project's life cycle. Using a BFO format provides a philosophical foundation as well as an automatic methodology for building a construction ontology. It also can support its integration with other domain ontologies. The developed ontology can facilitate the information flow as well as knowledge management for the construction industry, which can promote the implementation of *Construction 4.0*. The study is limited in terms of the number of interviews as well as the level of concepts, i.e., they can be further detailed.

Chapter 7: Conclusion and Future Work

7.1 Conclusions

The thesis aims to determine currently used tools to exchange information in the construction industry and evaluate the effectiveness of these tools, the extent of adoption of VSM, and develop a framework for VSM in CSC. A survey was conducted to collect data from industry participants. It was found that Alberta's construction industry mainly relies on emails, meetings, phone calls, and face to face discussions as a means of communication. The email has the highest frequency use index of 91%, followed by meetings, phone calls, correspondence, and IMS, at 80%, 69%, 56%, and 31%, respectively. We also find that most of the information within an organization stays at the individual employee level and is unlikely to be stored or shared formally with others. This hinders the transfer of construction knowledge from tacit to explicit knowledge, which impacts knowledge capitalization, innovation, and value creation. The construction industry in Alberta hasn't widely adopted VSM or other lean management techniques. Interviews with industry experts are conducted to determine the methods used to improve construction processes efficiency. It was found the industry hasn't yet adopted tools to identify and eliminate wastes, including lean management tools and VSM.

To determine the effectiveness of VSM methodology in CSC, case studies in procurement and tender phases are implemented. The results show that the traditional VSM is an effective tool to improve repetitive processes at the nano and micro levels. However, an efficient information flow system is required for an effective mapping methodology at the meso and macro levels. Taking into consideration the unique characteristics of construction projects, the study proposes a framework that introduces VSM to the planning phase of the projects to identify and eliminate wastes before the execution phase; it also implements VSM during the execution phase to monitor and measure performance. In a case study, the results show project execution plan was improved by reducing NVAT from 76.3% in the original plan to 29.5% in PVSM, and the actual one is 29.7%. An ontology is developed for the developed VSM framework using the BFO structure to facilitate its automation and communication with other ontologies. Implementing VSM to identify and eliminate wastes as well as monitor the progress of the future state map during installation can support the Critical Path Method (CPM) and other project management tools, such as scheduling and planning, that are being used to plan, monitor and control construction projects.

After completing the case studies, it was observed that the implementation of improvements in future state VSM can be a challenge especially when technology or investment is required such as purchasing or modifying ERP systems. Moreover, most processes' stakeholders are not familiar with the VSM and other lean tools. Lean education is needed, and it is recommended to assign personnel who is familiar with VSM and the organization processes to manage its implementation. The percentages of non-value-added activities were relatively high. It seems that the wastes are normalized in the processes; mapping the processes and discussing the wastes provides a "lens" for the process stakeholders to identify the wastes and understand the differences between value-added and non-value-added activities. VSM can also support exposing the problems and the root causes of the wastes which provides a lean "lens" for process stakeholders to eliminate wastes. An efficient tool to implement VSM is needed and can facilitate the process.

An ontology for construction knowledge is developed to support structuring CSC data and integrate it with other domain ontologies. In developing the ontology, BFO structure is followed, which is a mature ontology widely used in many domains, ISO 12006-2 (2015) recommendations are implemented, and domain experts are interviewed for the ontology development and evaluation. The ontology establishes high-level concepts of construction knowledge. It does not cover all construction concepts, but it can form a framework to structure the construction data, which supports the integration of the construction value chain by streamlining its information flow and knowledge management.

VSM has been widely applied in many sectors since the latter half of the 20^{th} century, but it is still implemented improperly in many cases; for example, only the current state map is developed and the future state map is ignored. Such inadequate application is due to the weakness of the traditional VSM and lack of standardization which allows such improper implementation, [79]. Moreover, implementing traditional VSM in construction face many challenges due to the characteristics of construction projects such as unique projects, non-repetitive processes where future state map cannot be applied, and multiple partners are involved in a single process. The study developed a framework that introduces VSM to the planning phase of the project and use it as a monitoring tool during the execution phase. Information flow is key in VSM. Mapping processes that involve multiple partners requires proper structuring of the information to facilitate its mapping. Ontology is a promising approach in information and knowledge management. However, the construction industry lacks a standardized methodology for ontology development as well as an ontology that covers all project phases. The study developed an upper construction ontology using the BFO structure to support its integration with other domain ontologies. The traditional VSM methodology can be applied for repetitive processes which are mainly related to the administrative offsite activities while a developed framework can be implemented in non-repetitive ones. The two VSM methodologies, i.e traditional and develop, can support mapping the majority of the construction processes, and the construction ontology can structure projects and processes data throughout all project phases. The VSM framework and construction ontology can support the development of a VSM framework which can be a step towards a standardized VSM methodology.

7.2 Study Limitations

Following are the major study limitations:

- The survey response rate is low. A higher response rate will be required to generalize the results.
- Interviews, regarding the use of lean management tools and ontology development, should be completed with a larger group of industry experts and in other geographical areas.
- More case studies should be completed for the VSM framework and in other construction sectors such as commercial and residential to optimize and integrate it with other project management tools

7.3 Future Work

The research undertaken in this dissertation demonstrates an approach to integrate the construction supply chain and enhance its performance by developing VSM and knowledge management frameworks. The summary of the thesis and future works are shown in Figure 33. Following are recommendations for future works:

- The VSM framework should be implemented in more case studies to support its generalization and then standardization. The case studies will be implemented in various industrial, commercial and institutional projects throughout the project phases which include design, construction execution, procurement and commissioning. The case studies' results will be used to optimize the framework.

- Artificial intelligence and machine learning can be utilized in the VSM framework to support "proactive" planning by identifying and eliminating wastes during the planning phase of the project. Also, VSM can be used to map and support other project management tools such as the *critical path method* (CPM).
- The developed ontology is a first step towards a detailed ontology that covers the majority of the construction concepts. Future work will be focusing on further developing and detailing the ontology through interviews with industry and academic experts. Also, the ontology should be socialized with experts in other regions to standardize it.
- The construction developed ontology was built following the BFO structure. Future work will focus on integrating it with other domain ontologies that have a similar structure. This can facilitate the integration of the construction supply chain as well as information flow across industries.
- The survey and interviews for information flow tools and efficiency improvement techniques can be conducted in other geographical areas, and the results should be compared to this study.
- The industry has realized the need to integrate its supply chain, so many project delivery models and approaches such as Integrated Project Delivery (IPD), Early Contractor Involvement (ECI), and advanced Work Packaging (AWP) have been developed to promote collaboration among project partners, [197]-[198]-[199]. The main aspect of these models is bringing project partners, including downstream ones, to be involved in

the early phases of the project, i.e. planning and design phases. The developed ontology

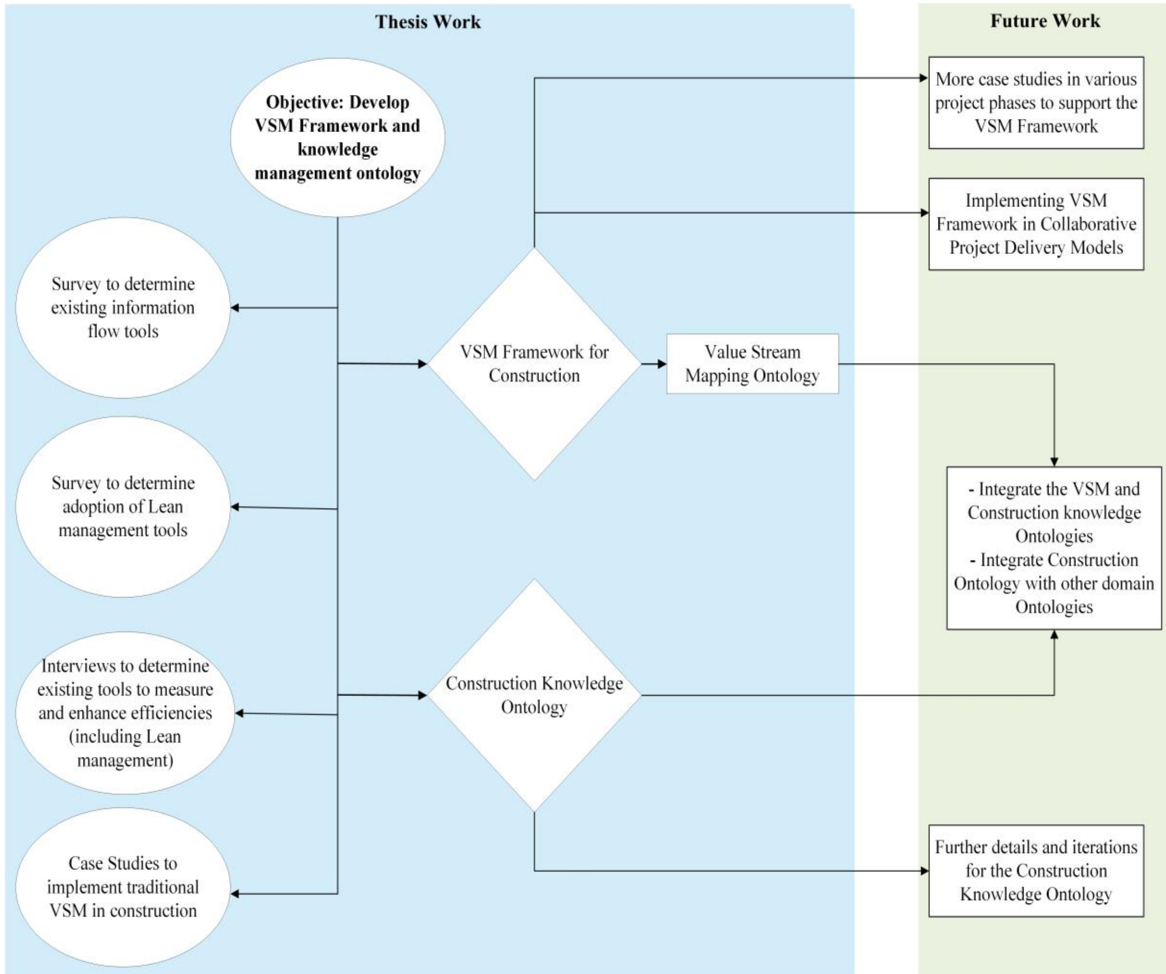


Figure 33: Summary of Thesis and Future Works

and VSM framework can support the collaborative project delivery models and project planning planning; following are examples of these models:

- Advanced Work Packaging (AWP)

AWP is defined as an approach to enhance project performance by aligning planning and execution. It develops deliverables, such as Construction Work Packages (CWP), Engineering Work Packages (EWP), and Installation Work Packages (IWP), in a collaborative manner during the early phases of the project, [200]. CWP carries construction information such as scope, quantities, quality, the safety that will be needed by the construction contractor to execute the work while the EWP carries the design and engineering information such as design drawings and specifications. IWPs are packages that are used by front end crews to execute the work, [199]. Therefore, the main aspects of AWP are early planning that involves engineering and construction contractors and breaking the project into packages that carry information to the downstream phases, as shown in Figure 34.

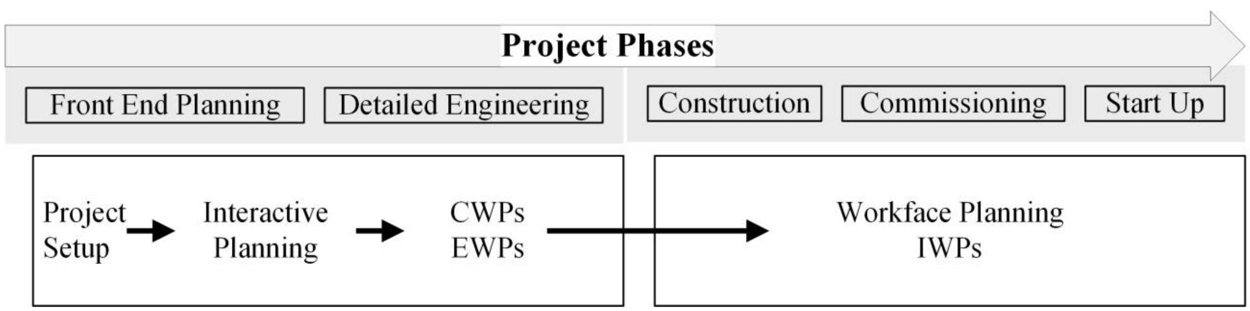


Figure 34: Advanced Work Packaging Model (adapted from [199])

The developed construction knowledge ontology can support the AWP model by facilitating the information flow and managing the data that can be adequately packaged to implement the AWP model. Moreover, the VSM framework can be implemented during the planning phase to eliminate waste and communicate the plan efficiently with front end crews.

(i) Integrated Project Delivery (IPD) Model

IPD includes the involvement of all key project partners such as owner, engineers, architect, and construction contractor from the outset of the project in an integrated manner, i.e. working as one team. The team plans the project collaboratively, and every partner executes his work as planned, [201]. IPD's main aspects are the collaborative work among project partners with trust, respect and suitable work relationship to achieve a common goal. However, the main challenges for the model are the inconsistency in structure organizations, various tools and techniques each partner brings in, [202]. The developed ontology that structures the construction knowledge can provide a consistent methodology to structure project data that can be used by all project partners. Moreover, the VSM framework can be utilized by project partners during the planning phase to identify and eliminate wastes and reduce project costs, which provide an incentive to all project partners as they share the cost-saving as per the IPD model.

(ii) Early Contractor Involvement (ECI) Model

ECI is defined as engaging the contractor from the early design phase of the project to influence design by its construction knowledge. The major aspects of ECI are promoting knowledge development and performance measurement to achieve continuous improvement in construction projects, [203]. The main advantage of ECI is early constructability input from the contactor can optimize the design by providing specific construction information on resource availability, promotes the collaboration between designers and contractors who are responsible for construction, and reduce project cost by designing to suit best construction methods, [204]. However, implementing the ECI model faces many challenges, such as culture change, inconsistent planning tools and data management systems among project partners, [204]. The VSM framework can support the ECI model by providing a planning tool to eliminate waste, monitor and control performance during the execution phase. Moreover, construction ontology can provide a consistent framework for knowledge management.

The developed knowledge management and VSM frameworks can support the collaborative models by structuring the project information and facilitate its retrieval and communication among project partners. The VSM framework can be used as a collaborative tool to plan, monitor and control the plan. In future work, the developed ontology and VSM can be implemented in collaborative project delivery models.

Bibliography

[1] Construction Industry Spending Worldwide From 2014 to 2025, (2017). https://www.statista.com/statistics/788128/construction-spending-worldwide/ (accessed May 30, 2020).

[2] J.C.P. Cheng, K.H. Law, H. Bjornsson, A. Jones, R. Sriram, A Service Oriented Framework for Construction Supply Chain Integration, Automation in Construction. 19 (2010) 245–260. https://doi.org/10.1016/j.autcon.2009.10.003.

[3] N.G.J.R. Vilasini, Implementing Value Stream Mapping Tool in the Construction Industry, International Research Conference on Sustainability in Built Environment. (2010) 256–265. https://doi.org/10.13140/RG.2.1.3178.5445.

[4] P.L. Le, W. Elmughrabi, T.M. Dao, A. Chaabane, Present Focuses and Future Directions of Decision-Making in Construction Supply Chain Management: a Systematic Review, International Journal of Construction Management. 20 (2020) 490–509. https://doi.org/10.1080/15623599.2018.1488089.

[5] G.M. Winch, How Innovative is Construction? Comparing Aggregated Data on Construction Innovation and Other Sectors - A Case of Apples and Pears, Construction Management and Economics. 21 (2003) 651–654. https://doi.org/10.1080/0144619032000113708.

[6] A. Mossman, Creating value: A Sufficient Way to Eliminate Waste in Lean Design and Lean Production, Lean Construction Journal. (2009) 13–23.

[7] J. Woetze, J. Mischke, M. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram, S. Brown, The

Construction Productivity Imperative | McKinsey, 2015. https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/the-construction-productivity-imperative (accessed May 30, 2020).

[8] A. Rivera, N. Le, J. Kashiwagi, D. Kashiwagi, Identifying the Global Performance of the Construction Industry, Journal for the Advancement of Performance Information and Value. 8 (2016) 7. https://doi.org/10.37265/japiv.v8i2.61.

[9] F. Barbosa, J. Woetzel, J. Mischke, M. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram, S. Brown, Re-inventing Construction In Brief (Mckinsey Global Institute), 2017.

[10] K. Zhou, T. Liu, L. Zhou, Industry 4.0: Towards Future Industrial Opportunities and Challenges, 12th International Conference on Fuzzy Systems and Knowledge Discovery FSKD, IEEE. (2015) 2147–2152. https://doi.org/10.1109/FSKD.2015.7382284.

[11] T.D. Oesterreich, F. Teuteberg, Understanding the Implications of Digitisation and Automation in the Context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry, Computers in Industry. 83 (2016) 121–139. https://doi.org/10.1016/j.compind.2016.09.006.

[12] Kagermann, W. Wahlster, J. Helbig, Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0, National Academy of Science and Engineering. (2013).

[13] M. Keller, M. Rosenberg, M. Brettel, N. Friederichsen, How Virtualization, Decentrazliation and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering. 8 (2014) 37–44.

[14] L. Da Xu, L. Duan, Big Data for Cyber Physical Systems in Industry 4.0: a Survey, Enterprise Information Systems. 13 (2019) 148–169. https://doi.org/10.1080/17517575.2018.1442934.

[15] V. Roblek, M. Meško, A. Krapež, A Complex View of Industry 4.0, SAGE. 6 (2016) 1–11. https://doi.org/10.1177/2158244016653987.

[16] A.W. Colombo, S. Karnouskos, O. Kaynak, Y. Shi, S. Yin, Industrial Cyberphysical Systems: A Backbone of the Fourth Industrial Revolution, IEEE Industrial Electronics Magazine. 11 (2017) 6–16. https://doi.org/10.1109/MIE.2017.2648857.

[17] A.W. Colombo, T. Bangemann, P. Stluka, R. Harrison, F. Jammes, Industrial Cloud-Based Cyber-Physical Systems, Springer, New York, 2014. https://doi.org/10.1007/978-3-319-05624-1.

[18] P. Leitão, S. Karnouskos, L. Ribeiro, J. Lee, T. Strasser, A.W. Colombo, Smart Agents in Industrial Cyber-Physical Systems, Proceedings of the IEEE. 104 (2016) 1086–1101. https://doi.org/10.1109/JPROC.2016.2521931.

[19] M.P. Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic, Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions, Future Generation Computer Systems. 369 (2013) 1645–1660.

[20] L. Da Xu, W. He, S. Li, Internet of Things in Industries: A Survey, IEEE Transactions on Industrial Informatics. 10 (2014) 2233–2243. https://doi.org/10.1109/TII.2014.2300753.

[21] C. Schroth, T. Janner, Web 2.0 and SOA: Converging Concepts Enabling the Internet of Services, IEEE Computer Society. 9 (2007) 36–41.

[22] J.Z. Reis, R.F. Gonçalves, The Role of Internet of Services (IoS) on Industry 4.0 Through the Service Oriented Architecture (SOA), FIP WG 5.7 International Conference, APMS 2018, Seoul, Korea,Proceedings, Part II. (2018). https://doi.org/10.1007/978-3-319-99707-0.

[23] K. Gopalakrishnan, A. Agrawal, A. Choudhary, Big Data in Building Information Modeling Research : Survey and Exploratory Text Mining, MOJ Civil Engineering. 3 (2017). https://doi.org/10.15406/mojce.2017.03.00087.

[24] A. Sawhney, M. Riley, J. Irizarry, Construction 4.0: An Innovation Platform for the Built Environment, in: Construction 4.0, Routledge, London and New York, 2020: p. 99. https://doi.org/10.1201/9780429398100-1.

[25] M. Wollschlaeger, T. Sauter, J. Jasperneite, The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0, IEEE Industrial Electronics Magazine. 12 (2017) 17–27. https://doi.org/10.1021/ie50124a022.

[26] S. Wang, J. Wan, D. Li, C. Zhang, Implementing Smart Factory of Industrie 4.0: An Outlook, International Journal of Distributed Sensor Networks. 4 (2016) 1–10. https://doi.org/10.1155/2016/3159805.

[27] C. Newman, D. Edwards, I. Martek, J. Lai, W.D. Thwala, I. Rillie, Industry 4.0 Deployment in the Construction Industry: a Bibliometric Literature Review and UK-based Case Study, Smart and Sustainable Built Environment. (2020). https://doi.org/10.1108/SASBE-02-2020-0016.

[28] C. Turner, J. Oyekan, L. Stergioulas, D. Griffin, Utilizing Industry 4.0 on the Construction Site: Challenges and opportunities, IEEE Transactions on Industrial Informatics. (2020)

1–1. https://doi.org/10.1109/tii.2020.3002197.

[29] T. Williams, Construction management : Emerging Trends and Technologies, First Edition, Delmar/Cengage Learning, 2010.

[30] H. Yu, T. Tweed, M. Al-Hussein, R. Nasseri, Development of Lean Model for House Construction Using Value Stream Mapping, Journal of Construction Engineering and Management. 135 (2009) 782–790. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:8(782).

[31] W. Shou, J. Wang, P. Wu, X. Wang, Y. Song, Application of Lean Production with Value Stream Mapping to the Blasting and Coating Industry, IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction. (2017) 217–224. https://doi.org/10.24928/2017/0308.

[32] Z. Zhou, Y.M. Goh, L. Shen, Overview and Analysis of Ontology Studies Supporting Development of the Construction Industry, Journal of Computing in Civil Engineering. 30 (2016) 1–14. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000594.

[33] Government of Canada- Statistics, Canada construction sector GDP 2018 | Statista, (2019). https://www.statista.com/statistics/519742/gdp-for-construction-sector-in-canada/ (accessed November 17, 2019).

[34] D. Simchi-Levi, P. Kaminsky, E. Simchi-Levi, R. Shankar, Designing and Managing the Supply Chain : Concepts, Strategies and Case Studies, in: McGraw-Hill, New York, 2000.

[35] J. Utomo, D.W.I. Hatmoko, S. Scott, Simulating the Impact of Supply Chain Management Practice on the Performance of Medium-Sized Building Projects, Construction

Management and Economics. (2010) 35–49. https://doi.org/10.1080/01446190903365632.

[36] P. Nai-Hsin, L. Yung-Yu, P. Nang-Fei, Enhancing Construction Project Supply Chains and Performance Evaluation Methods: a Case Study of a Bridge Construction Project, Canadian Journal of Civil Engineering. 37 (2010) 1094–1106. https://doi.org/10.1139/l10-047.

[37] W. O'Brien, K. London, R. Vrijhoef, Construction Supply Chain Modeling : a Research Review and Interdisciplinary Research Agenda, Journal of Operations Management. 3 (2004) 64–84. http://www.deakin.edu.au/dro/view/DU:30022947.

[38] P. Behera, R.P. Mohanty, A. Prakash, Understanding Construction Supply Chain Management, Production Planning & Control. 26 (2015) 1332–1350. https://doi.org/10.1080/09537287.2015.1045953.

[39] R. Liu, V.C. Chua, V. Com, Theoratical Digitalization of Information Flow in The Construction Supply Chain, International Journal of Management Research and Business Strategy. 5 (2016) 10–17.

[40] R. Vrijhoef, L. Koskela, The Four Roles of Supply Chain Management in Construction, European Journal of Purchasing & Supply Management. 6 (2000) 169–178. https://doi.org/10.1016/S0969-7012(00)00013-7.

[41] P. Konukcu, Selda; Anumba, Chimay; Carrillo, The Need for the Creation of Knowledge Chains in Construction, CIB W102 Conference on Performance and Knowledge Management. (2008) 179–191.

[42] Y. Gamil, I.A. Rahman, Identification of Causes and Effects of Poor Communication in

Construction Industry: A Theoretical Review, Emerging Science Journal. 1 (2017) 239–247. https://doi.org/10.28991/ijse-01121.

[43] A.R.J. Dainty, G.H. Briscoe, S.J. Millett, Subcontractor Perspectives on Supply Chain Alliances, Construction Management and Economics. 19 (2001) 841–848. https://doi.org/10.1080/01446190110089727.

[44] G. Briscoe, A. Dainty, Construction Supply Chain Integration: An Elusive Goal?, Supply Chain Management: An International Journal. 10 (2005) 319–326. https://doi.org/10.1108/13598540510612794.

[45] A. Segerstedt, T. Olofsson, Supply Chains in the Construction Industry, Supply Chain Management: An International Journal. 15 (2010) 347–353. https://doi.org/10.1108/13598541011068260.

[46] B. Jørgensen, S. Emmitt, Lost in transition: the Transfer of Lean Manufacturing to Construction, Engineering, Construction and Architectural Management. 15 (2008) 383–398. https://doi.org/10.1108/09699980810886874.

[47] D.T. Matt, D. Krause, R. Rauch, Adaptation of the Value Stream Optimization Approach to Collaborative Company Networks in the Construction Industry, Procedia CIRP. 12 (2013) 402–407. https://doi.org/10.1016/j.procir.2013.09.069.

[48] C.-H. Ko, J.-D. Kuo, Making Formwork Construction Lean, Journal of Civil Engineering and Management. 21 (2015) 444–458. https://doi.org/10.3846/13923730.2014.890655.

[49] A. Sawhney, M. Riley, J. Irizarry, Construction 4.0: An Innovation Platform for the Built Environment, in: Routledge, London and New York, 2020: p. 67.

[50] O. Zwikael, S. Globerson, Evaluating the Quality of Project Planning: A model and field results, International Journal of Production Research. 42 (2004) 1545–1556. https://doi.org/10.1080/00207540310001639955.

[51] O. Zwikael, Critical Planning Processes in Construction Projects, Construction Innovation. 9 (2009) 372–387. https://doi.org/10.1108/14714170910995921.

[52] M. Rother, J. Shook, Learning to See: Value Stream Mapping to Create Value and Eliminate MUDA, Lean Enterprise Institute, Cambridge, 1999.

[53] C. Oberhausen, P. Plapper, Value Stream Management in the Lean Manufacturing Laboratory, Procedia CIRP. 32 (2015) 144–149. https://doi.org/10.1016/j.procir.2015.02.087.

[54] Ł. Dekier, The Origins and Evolution of Lean Management System, Journal of International Studies. 5 (2012) 46–51. https://doi.org/10.14254/2071-8330.2012/5-1/6.

[55] J.P. Womack, D.T. Jones, D. Roos, The Machine That Changed the World: The Story of Lean Production-- Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry, Simon and Schuster, 2007. https://doi.org/0743299795.

[56] T. Ohno, Toyota Production System: Beyond Large-Scale Production, 1978.

[57] J. Liker, The Toyota Way: 14 Management Principles from the Worlds Greatest Manufacturer, McGraw-Hill, New York, 2004.

[58] A Brief History of Lean, Lean Enterprise Institute. (2019). https://www.lean.org/WhatsLean/History.cfm (accessed December 9, 2019).

[59] J. Kilpatrick, Lean Principles, Utah Manufacturing Extension. (2003) 1–5.

[60] G. Shang, L. Pheng, The Toyota Way Model: an Alternative Framework for Lean Construction, Total Quality Management & Business Excellence. 25 (2014) 664–682. https://doi.org/10.1080/14783363.2013.820022.

[61] S. Sarhan, A. Fox, Barriers to Implementing Lean Construction in the UK Construction Industry, The Built & Human Environment Review. 6 (2013) 1–17.

[62] H.J. Harrington, Business Process Improvement: The Breakthrough Strategy for Total Quality, Productivity, and Competitiveness, McGraw Hill Professional, 1991. http://books.google.com/books?id=cf4xJJabZbsC&pgis=1 (accessed November 24, 2019).

[63] T. Davenport, Process Innovation: Reengineering Work Through Information Technology, Harvard Business School Press, 1992. https://doi.org/10.1111/j.1467-9310.1995.tb01348.x.

[64] U.S. Bititci, D. Muir, Business Process Definition : a Bottom-up Approach, International Journal of Operations and Production Management. 17 (1997) 365–374.

[65] H. Johansson, Business Process Reengineering : Breakpoint Strategies for Market Dominance, Wiley, New York, 1993. https://ezp.lib.unimelb.edu.au/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat00006a&AN=melb.b1801574&site=eds-live (accessed November 24, 2019).

[66] H.K. Kalman, Process Mapping: Tools, Techniques, & Critical Success Factors, Performance Improvement Quarterly. 15 (2008) 57–73. https://doi.org/10.1111/j.1937-8327.2002.tb00265.x.

[67] T. Rohac, M. Januska, Value Stream Mapping Demonstration on Real Case Study,

Procedia Engineering. 100 (2015) 520–529. https://doi.org/10.1016/j.proeng.2015.01.399.

[68] K. Martin, M. Osterling, Value Stream Mapping : How to Visualize Work and Align Leadership for Organizational Transformation, First Edition, McGraw-Hill Education, 2013.

[69] V. Rosenbaum, Sergio ;Toledo, Mauricio ; González, Improving Environmental and Production Performance in Construction Projects Using Value-Stream Mapping: Case Study, Journal of Construction Engineering and Management. 140 (2014) 1–12. https://doi.org/10.1061/(ASCE)CO.1943-7862.

[70] J.C. Chen, R.A. Cox, Value Stream Management for Lean Office—A Case Study, American Journal of Industrial and Business Management. 02 (2012) 17–29. https://doi.org/10.4236/ajibm.2012.22004.

[71] Y. Monden, Toyota Production System: An Integrated Approach to Just-in-Time, Fourth Edition, CRC Press, Boca Raton, 2011. https://content.taylorfrancis.com/books/download?dac=C2009-0-14129-1&isbn=9781466504516&format=googlePreviewPdf (accessed October 26, 2019).

[72] J. P.Womack, Daniel T.Jones, Lean Thinking - Banish waste and Create Wealth In Your Cooperation, Second Edition, Productivity Press, New York, 2003.

[73] N.A.A. Rahman, S.M. Sharif, M.M. Esa, Lean Manufacturing Case Study with Kanban System Implementation, Procedia Economics and Finance. 7 (2013) 174–180. https://doi.org/10.1016/S2212-5671(13)00232-3.

[74] R. Sundar, A.N. Balaji, R.M. Satheesh Kumar, A Review on Lean Manufacturing

Implementation Techniques, Procedia Engineering. 97 (2014) 1875–1885. https://doi.org/10.1016/j.proeng.2014.12.341.

[75] C.N. Johnson, The Benefits of PDCA, Use this Cycle for Continual Process Improvement, Quality Progress, Business Premium Collection. 35 (2002) 120.

[76] Y. Sugimori, K. Kusunoki, F. Cho, S. Uchikawa, Toyota Production System and Kanban System Materialization of Just-in-Time and Respect-for-Human System, International Journal of Production Research. 15 (1977) 553–564. https://doi.org/10.1080/00207547708943149.

[77] J. Womack, D. Jones, D. Roos, The Machine That Changed the World, Rawson Associates, New York, 1990. https://www.lean.org/Bookstore/ProductDetails.cfm?SelectedProductID=160 (accessed November 14, 2020).

[78] J. Wolmack, D. Jones, Lean Thinking: Banish Waste and Create Wealth in Your Corporation, First Edition, Simon & Schuster, New York, 1996. https://www.amazon.ca/Thinking-James-Jones-Daniel-Wolmack/dp/0684810352/ref=sr_1_1?dchild=1&keywords=Lean+Thinking+1996&qid=1605391903&sr=8-1 (accessed November 14, 2020).

[79] L.F. Romero, A. Arce, Applying Value Stream Mapping in Manufacturing: A Systematic Literature Review, International Federation of Automatic Control, Hosting by Elsevier Ltd. 50 (2017) 1075–1086. https://doi.org/10.1016/j.ifacol.2017.08.385.

[80] P.S. Gill, Application of Value Stream Mapping to Eliminate Waste in an Emergency Room, Global Journal of Medical Research. 12 (2012) 1–7.

https://doi.org/10.1504/IJISE.2009.023539.

[81] B. Villareal, F. Garza, I. Rosas, D. Garcia, An Introduction to Distribution Operational Efficiency, International Journal of Industrial Engineering : Theory Applications and Practice. 19 (2012) 278–288.

[82] D. Musat, P. Rodríguez, Value Stream Mapping Integration in Software Product Lines, ACM International Conference Proceeding Series. (2010) 110–111. https://doi.org/10.1145/1961258.1961285.

[83] S. Tyagi, S. Vadrevu, Immersive Virtual Reality to Vindicate the Application of Value Stream Mapping in an US-based SME, International Journal of Advanced Manufacturing Technology. 81 (2015) 1259–1272. https://doi.org/10.1007/s00170-015-7301-1.

[84] H. De Steur, J. Wesana, M.K. Dora, D. Pearce, X. Gellynck, Applying Value Stream Mapping to Reduce Food Losses and Wastes in Supply Chains: A Systematic Review, IFAMA World Conference - Aarhus, Denmark. 58 (2016) 1–17. https://doi.org/10.1016/j.wasman.2016.08.025.

[85] F. Pasqualini, P.A. Zawislak, Value Stream Mapping in Construction : a Case Study in a Brazilian Construction Company, 13th International Group for Lean Construction Conference. (2005) 117–125. https://www.dropbox.com/s/yrfuf5jk1v0eocx/14_034_Pasqualini_Zawislak.pdf (accessed December 28, 2017).

[86] L. Koskela, Application of the New Production Philosophy to Construction, Stanford University. 72 (1992).

[87] W. Shou, Enhanced Value Stream Mapping for Improving Turnaround Process Efficiency in Oil and Gas Industry, Curtin University, 2018.

[88] L.S. Pothen, S. Ramalingam, Applicability of Value Stream Mapping and Work Sampling in an Industrial Project in India, IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers. 1 (2018) 516–526. https://doi.org/10.24928/2018/0263.

[89] P.V. Ramani, L.K.L. KSD, Application of Lean in Construction Using Value Stream Mapping, Engineering, Construction and Architectural Management. (2019). https://doi.org/10.1108/ECAM-12-2018-0572.

[90] T.Q. Nguyen, S.S. Waikar, A Relook at Plan Reliability Measurements in Lean Construction and New Metrics From Digitized Practical Implementation, IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers. 2 (2018) 1037–1046. https://doi.org/10.24928/2018/0216.

[91] L. Melo, V. Lima, R. Melo, Value Stream Mapping: A Case Study in Structural Masonry, IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction. (2017) 755–762.

[92] P.S.P. Fontanini, F.A. Picchi, S.A. Loureiro, O.F. Lima, A.T. Folch, Simulating a Construction Supply Chain- Preliminary Case Study of Pre-cast Elements, Proceedings of IGLC16: 16th Annual Conference of the International Group for Lean Construction. (2008) 371–380.

[93] S. Wang, J. Tang, Y. Zou, Q. Zhou, Research on Production Process Optimization of Precast Concrete Component Factory Based on Value Stream Mapping, Engineering, Construction and Architectural Management. 27 (2019) 850–871. https://doi.org/10.1108/ECAM-10-2018-0455.

[94] T. Xiaosheng, F. Hamzeh, Precast Concrete Building, in: Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC28), Berkeley, CA, USA, 2020: pp. 1–12. https://doi.org/10.24928/2020/0027.

[95] G. Heravi, M.F. Kebria, M. Rostami, Integrating the Production and the Erection Processes of Pre-fabricated Steel Frames in Building Projects Using Phased Lean Management, Engineering, Construction and Architectural Management. (2019). https://doi.org/10.1108/ECAM-03-2019-0133.

[96] R.T. Honório, J.M.C. Da Costa, S.M.B. Serra, Evaluation of Supply and Service of Steel Assembly of Structures, 22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014. (2014) 1057–1068.

[97] B. Bekdik, D. Hall, S. Aslesen, Off-Site Prefabrication: What Does It Require From the Trade Contractor?, Proceedings of 24th Annual Conference of the International Group for Lean Construction (IGLC), Boston, MA, USA. (2016) 43–52. www.iglc.net.

[98] M. Moghadam, M. Al-Hussein, Resource Optimization for Modular Construction through Value Stream Map Improvement, 21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013. 1 (2013) 706–715.

[99] F. Alsakka, K. Eid, T. Narciss, F. Hamzeh, Integrating Lean Into Modular Construction: A

Detailed Case Study of Company X, Proceedings of 24th Annual Conference of the International Group for Lean Construction (IGLC), Boston, MA, USA. (2016) 23–32. https://doi.org/10.13140/RG.2.1.3487.0005.

[100] S.L. Kemmer, T.C.L. Da Alves, M. Macedo, V.N. De Marcos, J.P. De Barros Neto, Lean Office at a Construction Company, Proceedings of IGLC17: 17th Annual Conference of the International Group for Lean Construction. (2009) 43–52.

[101] D.F. Garrett, J. Lee, Lean Construction Submittal Process—A Case Study, Quality Engineering. 23 (2010) 84–93. https://doi.org/10.1080/08982112.2010.495100.

[102] A.R. Vieira, N. Cachadinha, Lean Construction and Sustainability - Complementary Paradigms? a Case Study, Proceeding of 19th Annual Conference of IGLC. (2011) 611–621.

[103] A. Francis, A. Thomas, Exploring the Relationship Between Lean Construction and Environmental Sustainability: A Review of Existing Literature to Decipher Broader Dimensions, Journal of Cleaner Production. 252 (2020) 119913. https://doi.org/10.1016/j.jclepro.2019.119913.

[104] D. Lorenzon dos Santos, R. Giglio, A.L. Helleno, L.M.S. Campos, Environmental Aspects in VSM: a Study About Barriers and Drivers, Production Planning and Control. 30 (2019) 1239–1249. https://doi.org/10.1080/09537287.2019.1605627.

[105] K.P. Leite, J. De Paula Barros Neto, Value Stream in Housing Design, 21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013. (2013) 414–423.

[106] M. Michaud, D. Forgues, J. Meyer, C. Ouellet-Plamondon, A Case Study on Improving Standardization in the Conception Phase by Developing Tools and Protocols, 27th Annual Conference of the International Group for Lean Construction, IGLC 2019. (2020) 927–936. https://doi.org/10.24928/2019/0176.

[107] A. Aka, F. Emuze, D. Das, Mapping Waste in the Structural Design Process in South African projects, IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction. (2017) 475–482. https://doi.org/10.24928/2017/0053.

[108] F. Cavdur, B. Yagmahan, E. Oguzcan, N. Arslan, N. Sahan, Lean Service System Design: a Simulation-based VSM Case Study, Business Process Management Journal. 25 (2019) 1802–1821. https://doi.org/10.1108/BPMJ-02-2018-0057.

[109] P. Wang, P. Wu, X. Wang, X. Chen, T. Zhou, Developing Optimal Scaffolding Erection Through the Integration of Lean and Work Posture Analysis, Engineering, Construction and Architectural Management. (2020). https://doi.org/10.1108/ECAM-04-2019-0193.

[110] P. Wang, P. Wu, H.L. Chi, X. Li, Adopting Lean Thinking in Virtual Reality-based Personalized Operation Training Using Value Stream Mapping, Automation in Construction. 119 (2020) 103355. https://doi.org/10.1016/j.autcon.2020.103355.

[111] C. Oberhausen, P. Plapper, A Standardized Value Stream Management Method for Supply Chain Networks, Proceedings of COMA'16 International Conference on Competitive Manufacturing. 15 (2016) 428–433. https://doi.org/10.1017/CBO9781107415324.004.

[112] S.M.S. Jack R. Meredith, Samuel J. Mantel, Jr., Project Management: A Managerial Approach, 6th Edition, Wiley, New York, 2006.

https://books.google.ca/books?hl=en&lr=&id=ipZXDwAAQBAJ&oi=fnd&pg=PA1&dq=Project+Management+–+A+Managerial+Approach&ots=Qwq8uJMzoW&sig=CKrzgxF2oSUuqTznavFjJkV1sCY#v=onepage&q=Project Management – A Managerial Approach&f=false (accessed January 18, 2020).

[113] R. Arp, B. Smith, A.D. Spear, Introduction to Basic Formal Ontology I: Continuants, MIT Press Scholarship Online. May (2016) 85–120. https://doi.org/10.7551/mitpress/9780262527811.001.0001.

[114] I.F. Cruz, H. Xiao, The Role of Ontologies in Data Integration, International Journal of Engineering Intelligent Systems for Electrical Engineering and Communications. 13 (2005) 245–252.

[115] M. Argüello, M. Lees, H.C. Ong, An Ontology-driven Approach to Construction Knowledge Exchange, Proceedings of the 3rd International SCRI Symposium. (2006) 572–588.

[116] R. Arp, B. Smith, A.D. Spear, Building Ontologies With Basic Formal Ontology, MIT Press Scholarship Online. (2015) 21–24.

[117] R. Mizoguchi, Towards Ontology Engineering, Journal of Japanese Society for Artificial Intelligence. 13 (1998) 9–10.

[118] C.R. Huang, R.Y. Chang, H.P. Lee, Sinica BOW (Bilingual Ontological Wordnet): Integration of Bilingual WordNet and SUMO, Proceedings of the 4th International Conference on Language Resources and Evaluation, LREC 2004. (2004) 1553–1556. https://doi.org/10.1017/cbo9780511676536.012.

[119] H.A.J. de Ridder, J.W.F. Wamelink, An Ontology To Improve the Knowledge Management For Construction, Second International Conference World of Construction Project Management. (2007) 1–9.

[120] R. Arp, B. Smith, A. Spear, Introduction to Basic Formal Ontology II: Occurrents, MIT Press Scholarship Online. May (2016) 121–130. https://doi.org/10.7551/mitpress/9780262527811.001.0001.

[121] Z. Turk, Elements of an Ontology of Construction Informatics, Proceedings of the European Conference on Information and Communication Technology Advances and Innovation in the Knowledge Society (ESM@RT 2002 in Collaboration with CISEMIC 2002). Part A (2002) 155–167.

[122] T.A. El-Diraby, C. Lima, B. Feis, Domain Taxonomy for Construction Concepts: Toward a Formal Ontology for Construction Knowledge, Journal of Computing in Civil Engineering. 19 (2005) 394–406. https://doi.org/10.1061/(asce)0887-3801(2005)19:4(394).

[123] T.E. El-Diraby, Domain Ontology for Construction Knowledge, Journal of Construction Engineering and Management. 139 (2012) 768–784. https://doi.org/10.1061/(asce)co.1943-7862.0000646.

[124] S. Dhakal, L. Zhang, X. Lv, Ontology-based Semantic Modelling to Support Knowledge-based Document Classification on Disaster-Resilient Construction Practices, International Journal of Construction Management. (2020) 1–20. https://doi.org/10.1080/15623599.2020.1765097.

[125] X. Xing, B. Zhong, H. Luo, H. Li, H. Wu, Ontology for Safety Risk Identification in

Metro Construction, Computers in Industry. 109 (2019) 14–30. https://doi.org/10.1016/j.compind.2019.04.001.

[126] W. Fang, L. Ma, P.E.D. Love, H. Luo, L. Ding, A. Zhou, Knowledge Graph for Identifying Hazards on Construction Sites: Integrating Computer Vision with Ontology, Automation in Construction. 119 (2020) 1–10. https://doi.org/10.1016/j.autcon.2020.103310.

[127] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, L. He, A Scientometric Analysis and Critical Review of Construction Related Ontology Research, Automation in Construction. 101 (2019) 17–31. https://doi.org/10.1016/j.autcon.2018.12.013.

[128] T. Le, F. Hassan, C. Le, H.D. Jeong, Understanding Dynamic Data Interaction Between Civil Integrated Management Technologies: a Review of Use Cases and Enabling Techniques, International Journal of Construction Management. (2019) 1–22. https://doi.org/10.1080/15623599.2019.1678863.

[129] S. Kumar, V.K. Bansal, GIS-based Locational Evaluation of Infrastructure Facilities in Hilly Regions: a Case Study of an Institute Campus, International Journal of Construction Management. (2019) 1–20. https://doi.org/10.1080/15623599.2019.1604114.

[130] Y. Alani, N. Dawood, S. Rodriguez, H. Dawood, Whole Life Cycle Construction Information Flow Using Semantic Web Technologies: A Case for Infrastructure Projects, Proceedings 37th CIB W78 Information Technology for Construction Conference (CIB W78)- São Paulo, Brazil. (2020) 141–155. https://doi.org/10.46421/2706-6568.37.2020.paper011.

[131] ISO15926-13:(2018) Industrial Automation Systems and Integration — Integration of

Life-cycle Data for Process Plants Including Oil and Gas Production Facilities, (ISO), International Organization for Standarization. (2018). https://doi.org/10.1177/1063293X19894041.

[132] C. Igwe, F. Nasiri, A. Hammad, Construction Workspace Management: Critical Review and Roadmap, International Journal of Construction Management. (2020) 1–14. https://doi.org/10.1080/15623599.2020.1756028.

[133] BFO-Website, Basic Formal Ontology Website, (2019). https://basic-formal-ontology.org/users.html (accessed July 9, 2019).

[134] T.R. Gruber, A Translation Approach to Portable Ontology Specifications. Knowledge Acquisition, Knowledge System Laboratory, Stanford University. 5 (1993) 199–220. https://doi.org/10.1006/knac.1993.1008.

[135] V. Kumar, A. Khamis, S. Fiorini, J.L. Carbonera, A.O. Alarcos, M. Habib, P. Goncalves, L.I. Howard, J.I. Olszewska, Ontologies for Industry 4.0, The Knowledge Engineering Review. 34 (2019) 1–14. https://doi.org/10.1017/S0269888919000109.

[136] V.W.Y. Tam, K.N. Le, C.N.N. Tran, I.M.C.S. Illankoon, A Review on International Ecological Legislation on Energy Consumption: Greenhouse Gas Emission Management, International Journal of Construction Management.(2019) 1–12. https://doi.org/10.1080/15623599.2019.1576259.

[137] X. Chang, R. Rai, J. Terpenny, Development and Utilization of Ontologies in Design for Manufacturing, Journal of Mechanical Design. 132 (2010) 1–12. https://doi.org/10.1115/1.4000697.

[138] International Organization for Standarization (ISO), ISO 12006-2 (E): Building Construction - Organization of Information about Construction Works, (2015).

[139] Q. Zou, E.G. Park, Linking Historical Collections in an Event-based Ontology, Digital Library Perspectives. 34 (2018) 262–275. https://doi.org/10.1108/DLP-02-2018-0005.

[140] J.W. Creswell, D.J. Creswell, Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, Second Edition, Sage, Thousand Oaks, CA, 2003. http://www.amazon.com/Research-Design-Qualitative-Quantitative-Approaches/dp/0761924426 (accessed December 7, 2019).

[141] J. Sale, L. Lohfeld, K. Brazil, Revisiting the Quantitative-Qualitative Debate: Implications for Mixed-Methods Research, Quality and Quantity. 36 (2002) 43–53. https://doi.org/10.1023/A.

[142] A. Onwuegbuzie, R. Johnson, The Validity Issue in Mixed Research, Research in the Schools, Mid-South Educational Research Association. 13 (2006) 48–63.

[143] N. Denszin, Y. Lincolin, Handbook of Qualitative Research, Second, Sage Publications, Thousand Oaks, CA, 1994. https://doi.org/10.1016/s0031-9406(05)61288-6.

[144] S. Ospina, Qualitative Research in Performing Arts Medicine, Encyclopedia of Leadership. (2004) 1280–1285.

[145] S. Kvale, Interviews: An Introduction to Qualitative Research Interviewing, Sage Publications, 1996. https://doi.org/10.1037/0022-3514.90.4.644.

[146] A.B. Kajornboon, Using Interviews as Research Instruments Annabel Bhamani Kajornboon Language Institute Chulalongkorn University, E-Journal for Research

Teachers. 2 (2005).

[147] P. Corbetta, Social Research : Theory , Methods and Techniques The Use of Documents, Sage Publications, London, 2003.

[148] D. Gray, Doing Research in the Real World, Sage Publications, London, 2004. https://ualberta.worldcat.org/title/doing-research-in-the-real-world/oclc/297231907 (accessed December 7, 2019).

[149] A. Bryman, Social Research Methods, Oxford Unversity Press, Oxford, 2001.

[150] C.D.S. Matthew David, Social Research: The Basics, Sage Publications, London, 2004. https://books.google.ca/books?id=QKE1DiqrSA4C&pg=PP1&lpg=PP1&dq=social+research+the+basics+david+sutton&source=bl&ots=_cjzG4O1yW&sig=ACfU3U1hvYgYXB4B5PiSXdkYoXyebmM7Sg&hl=en&sa=X&ved=2ahUKEwjiipXk9aTmAhXHrZ4KHXlmAYMQ6AEwB3oECAoQAQ#v=onepage&q=social resea (accessed December 7, 2019).

[151] S. Toor, G. Ofori, Grounded Theory as an Appropriate Methodology for Leadership Research in Construction, Proceedings of the CIB International Conference on Building Education and Research. (2008) 1816–1831.

[152] S.G. Naoum, Dissertation Research and Writing for Construction Students, Third Edition, Routledge, London and New York, 2013.

[153] W.B. Isaac, S., & Michael, Handbook in Research and Evaluation: a Collection of Principles, Methods, and Strategies Useful in the Planning, Design, and Evaluation of Studies in Education and the Behavioral Sciences, 3rd Edition, Educational and Industrial Testing Services, San Diego, California, 1995.

[154] A. Pinsonneault, K. Kraemer, Survey Research Methodology in Management Information Systems: An Assessment, Escholarship, University of California. (1993). https://escholarship.org/uc/item/6cs4s5f0.

[155] P. Salant, D.A. Dillman, How to Conduct Your Own Survey, Wiley, 1994.

[156] N. Mathers, N. Fox, A. Hunn, Surveys and Questionnaires, National Institute for Health Research. (2009) 1–48.

[157] N. Showkat, H. Parveen, Quantitative Methods : Survey, Quadrant-I (e-Text). (2017).

[158] B.F. Shareia, Qualitative and Quantitative Case Study Research Method on Social Science: Accounting Perspective, International Journal of Social, Management, Economics, and Business Engineering. 9 (2015) 3873–3877.

[159] G. Anderson, Fundamentals of Educational Research, Falmer Press, London, 1993.

[160] R. Yin, Case Study Research: Design and Methods. London:, Sage Publications, London, 1989.

[161] Edmonton Construction Association, (2018). https://www.edmca.com/ (accessed June 3, 2018).

[162] A. Agresti, C. Franklin, Statistics: The Art and Science of Learning from Data, Second, Pearson, Upper Sandle River, 2009. https://www.pearson.com/us/higher-education/product/Agresti-Statistics-The-Art-and-Science-of-Learning-from-Data-3rd-Edition/9780321755940.html.

[163] M.M. Marzouk, T.I. El-Rasas, Analyzing Delay Causes in Egyptian Construction Projects, Journal of Advanced Research. 5 (2014) 49–55.

https://doi.org/10.1016/j.jare.2012.11.005.

[164] S.A. Assaf, S. Al-Hejji, Causes of Delay in Large Construction Projects, International Journal of Project Management. 24 (2006) 349–357. https://doi.org/10.1016/j.ijproman.2005.11.010.

[165] A.N. Javernick-Will, W.R. Scott, Who Needs to Know What? Institutional Knowledge and International Projects, Journal of Construction Engineering and Management. 136 (2009) 546–557.

[166] C.P. Pathirage, D.G. Amaratunga, R.P. Haigh, Tacit knowledge and Organisational Performance: Construction Industry Perspective, Journal of Knowledge Management. 11 (2007) 115–126. https://doi.org/10.1108/13673270710728277.

[167] I. Nonaka, R. Toyama, N. Konno, SECI, Ba and Leadership: A Unified Model of Dynamic Knowledge Creation, Long Range Planning. 33 (2000) 5–34. https://doi.org/10.1016/S0024-6301(99)00115-6.

[168] L. Zhang, X. Chen, Role of Lean Tools in Supporting Knowledge Creation and Performance in Lean Construction, Procedia Engineering. 145 (2016) 1267–1274. https://doi.org/10.1016/j.proeng.2016.04.163.

[169] M. Sarshar, U. Isijdag, A Survey of ICT Use in the Turkish Construction Industry, Engineering, Construction and Architectural Management. 11 (2004) 238–247. https://doi.org/10.1108/09699980410547595.

[170] T.A.H.T. Barakat, A Hybrid Model of Communication and Information Management in Mega Construction Projects in Dubai Using a New Critical Success Factor Approach ,

PhD Thesis, Loughborough Univeristy, 2009. https://dspace.lboro.ac.uk/dspace/handle/2134/6384%5Cnhttps://dspace.lboro.ac.uk/2134/6384.

[171] K.I.A. Khan, R. Flanagan, S.-L. Lu, Managing the Complexity of Information Flow for Construction Small and Medium-Sized Enterprises (CSMEs) Using System Dynamics and Collaborative Technologies, Proceedings 31st Annual ARCOM Conference, 7-9 September 2015. (2015) 1177–1186.

[172] M. Al Qady, A. Kandil, M. Asce, Document Management in Construction : Practices and Opinions, Journal of Construction Engineering and Management. 139 (2013) 1–7. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000741.

[173] F. Mellado, E.C.W. Lou, C.L.C. Becerra, Synthesising Performance in the Construction Industry: An Analysis of Performance Indicators to Promote Project Improvement, Engineering, Construction and Architectural Management. 27 (2019) 579–608. https://doi.org/10.1108/ECAM-09-2018-0419.

[174] S.B.S. Ahmad, F. Svalestuen, B. Andersen, O. Torp, A Review of Performance Measurement for Successful Concurrent Construction, Procedia - Social and Behavioral Sciences. 226 (2016) 447–454. https://doi.org/10.1016/j.sbspro.2016.06.210.

[175] M. Crotty, The Foundations of Social Research, SAGE Publications Ltd, London, UK, 1998. https://uk.sagepub.com/en-gb/eur/the-foundations-of-social-research/book207972 (accessed September 27, 2020).

[176] Z. Gao, M. Aslam, G. Smith, Strategies to Increase the Adoption Rate of Lean Construction, Associated Schools of Construction Proceedings of the 56th Annual

International Conference Strategies. 1 (2020) 364–372.

[177] W. Albalkhy, R. Sweis, Barriers to Adopting Lean Construction in the Construction Industry: a Literature Review, International Journal of Lean Six Sigma. (2020). https://doi.org/10.1108/IJLSS-12-2018-0144.

[178] M.H. Construction, Lean construction - Leveraging Collaboration and Advanced Practices to Increase Project Efficiency, 2013. http://www.ncbi.nlm.nih.gov/pubmed/21174905.

[179] H. Taherdoost, Validity and Reliability of the Research Instrument ; How to Test the Validation of a Questionnaire / Survey in a Research, International Journal of Academic Research in Management. 5 (2016) 28–36.

[180] Rasha Sayed Suleiman, Understanding Site Offices Challenges to Communicate and Exchange Information Using Technology in UK: Main Contractor Perspective, The University of Salford, 2019.

[181] A. Golyani, H.-Y. Hon, Information Handling in Construction Projects, Chalmers University of Technology, Sweden, 2010.

[182] T.A.H. Barakat, A hybrid model of Communication and Information Management in Mega Construction Projects in Dubai Using a New Critical Success Factor Approach, PhD Thesis, Loughborough Univeristy, 2009.

[183] T. Matti, L. Antti, Improving the Information Flow in the Construction Phase of a Construction Project, Proceedings of the Creative Construction E-Conference. (2020) 40–49. https://doi.org/10.3311/ccc2020-044.

[184] A.D. Leto, The Information Exchange in the Construction Sector in the Age of BIM: A

Multiple Case Study from Italy, IOP Conference Series: Materials Science and Engineering. 800 (2020). https://doi.org/10.1088/1757-899X/800/1/012036.

[185] N.S. Priyadharshini, K.S. Satheesh, Project Communication : Is Key To Productive Construction and It ' S Research Needs in the Future of Construction Engineering and Management, International Journal of Science, Technology & Management. 4 (2015) 1493–1499.

[186] L.Y. Shen, J. Li Hao, V.W.Y. Tam, H. Yao, A checklist for Assessing Sustainability Performance of Construction Projects, Journal of Civil Engineering and Management. 13 (2007) 273–281. https://doi.org/10.1080/13923730.2007.9636447.

[187] S. Onder, Lean Construction: Pull Planning Sessions in Two Different Settings, Worcester Polytechnic Institute. (2016) 1–49. https://web.wpi.edu/Pubs/E-project/Available/E-project-032516-092030/unrestricted/Lean_Coaching.pdf.

[188] A. De Meyer, C.H. Loch, M.T. Pich, Managing Project Uncertainty: From Variation to Chaos, IEEE Engineering Management Review. 30 (2002) 91–98. https://doi.org/10.1109/EMR.2002.1032403.

[189] The Associated General Contractors of America, Lean Construction Education Program Unit 5: Lean Supply Chain and Assembly Participant's, First Edition, Arlington, 2014.

[190] M.R. Perez, J. Gausemeier, D. Nordsiek, Ontology Development for a Manufacturing Data Base for Products with Graded Properties, Proceedings - International Conference on Information, Process, and Knowledge Management. (2009) 105–109. https://doi.org/10.1109/eKNOW.2009.8.

[191] WebVOWL Website, (2019). http://www.visualdataweb.de/webvowl/#file=Construction Ontology.owl (accessed August 3, 2019).

[192] K. Janowicz, S. Lohmann, S. Negru, F. Haag, T. Ertl, Visualizing Ontologies with VOWL, Sematic Web. 7 (2016) 399–419. https://doi.org/10.3233/SW-150200.

[193] R. Staab, Seffen; Studer, Handbook on Ontologies, 2nd Edition, Springer, 2009. https://doi.org/10.1007/978-3-662-04303-5.

[194] S. Lohmann, V. Link, E. Marbach, S. Negru, WebVOWL - Web-based Visualization of Ontologies, Springer International Publishing Switzerland. (2015) 154–158. https://doi.org/10.1007/978-3-319-17966-7 21.

[195] A. Gómez-Pérez, M. Fernández-López, O. Corcho, A. Gomez-Perez, Ontological Engeenering with Examples from the Areas of Knowledge Management, e-Commerce and the Semantic Web, 2010.

[196] R.G. Sargent, Verification and Validation of Simulation Models, Proceedings of the Winter Simulation Conference, WSC09: Winter Simulation Conference, Austin ,Texas December, IEEE. (2009) 162–176. https://doi.org/10.4018/978-1-60566-774-4.ch004.

[197] Z. Kahvandi, E. Saghatforoush, M. Alinezhad, F. Noghli, Integrated Project Delivery (IPD) Research Trends., Journal of Engineering, Project, and Production Management. 7 (2017) 99–114. https://doi.org/10.32738/jeppm.201707.0006.

[198] E. Scheepbouwer, A.B. Humphries, Transition in Adopting Project Delivery Method with Early Contractor Involvement, Transportation Research Record: Journal of the Transportation Research Board. (2011) 44–50. https://doi.org/10.3141/2228-06.

[199] O. Hamdi, Advanced Work Packaging from Project Definition through Site Execution: Driving Successful Implementation of WorkFace Planning, The University of Texas at Austin, 2013.

[200] CII - RT-272 - Enhanced Work Packaging: Design through WorkFace Execution, (2019). https://www.construction-institute.org/topic-summaries/rt-201-300/rt-272-enhanced-work-packaging-design-through (accessed November 12, 2019).

[201] AIA California Council, Integrated Project Delivery: A Guide, American Institute of Architects. (2007) 1–62. https://doi.org/10.1016/j.autcon.2010.09.002.

[202] M. El Asmar, M. Asce, A.S. Hanna, F. Asce, W.-Y. Loh, Quantifying Performance for the Integrated Project Delivery System as Compared to Established Delivery Systems, Journal of Construction Engineering and Management. 139 (2013). https://doi.org/10.1061/(ASCE).

[203] S.M. Song, Lingguang; Mohamed, Yasser; AbouRizk, Early Contractor Involvement in Design and Its Impact on Construction Schedule Performance, Journal of Management in Engineering. 4 (2009) 12–20. https://doi.org/10.1061/(ASCE)0742-597X(2009)25.

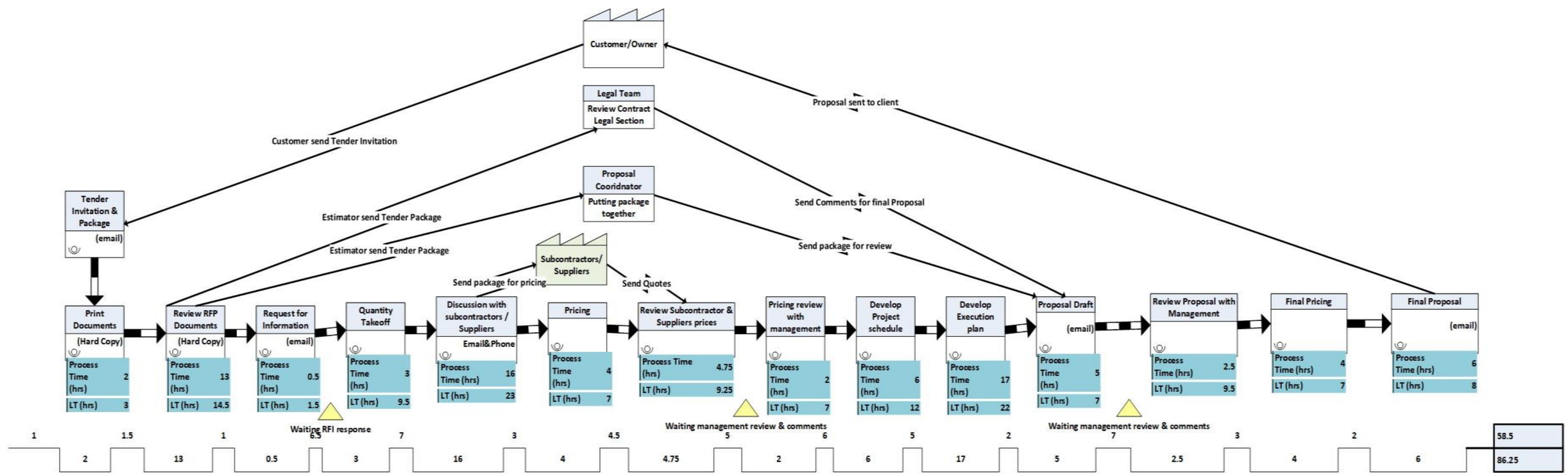
[204] M.M. Rahman, A. Alhassan, A contractor's Perception on Early Contractor Involvement, Built Environment Project and Asset Management. 2 (2012) 217–233. https://doi.org/10.1108/20441241211280855.

[205] Stanford-University-Website, Protege, (2019). https://protege.stanford.edu/ (accessed July 7, 2019).

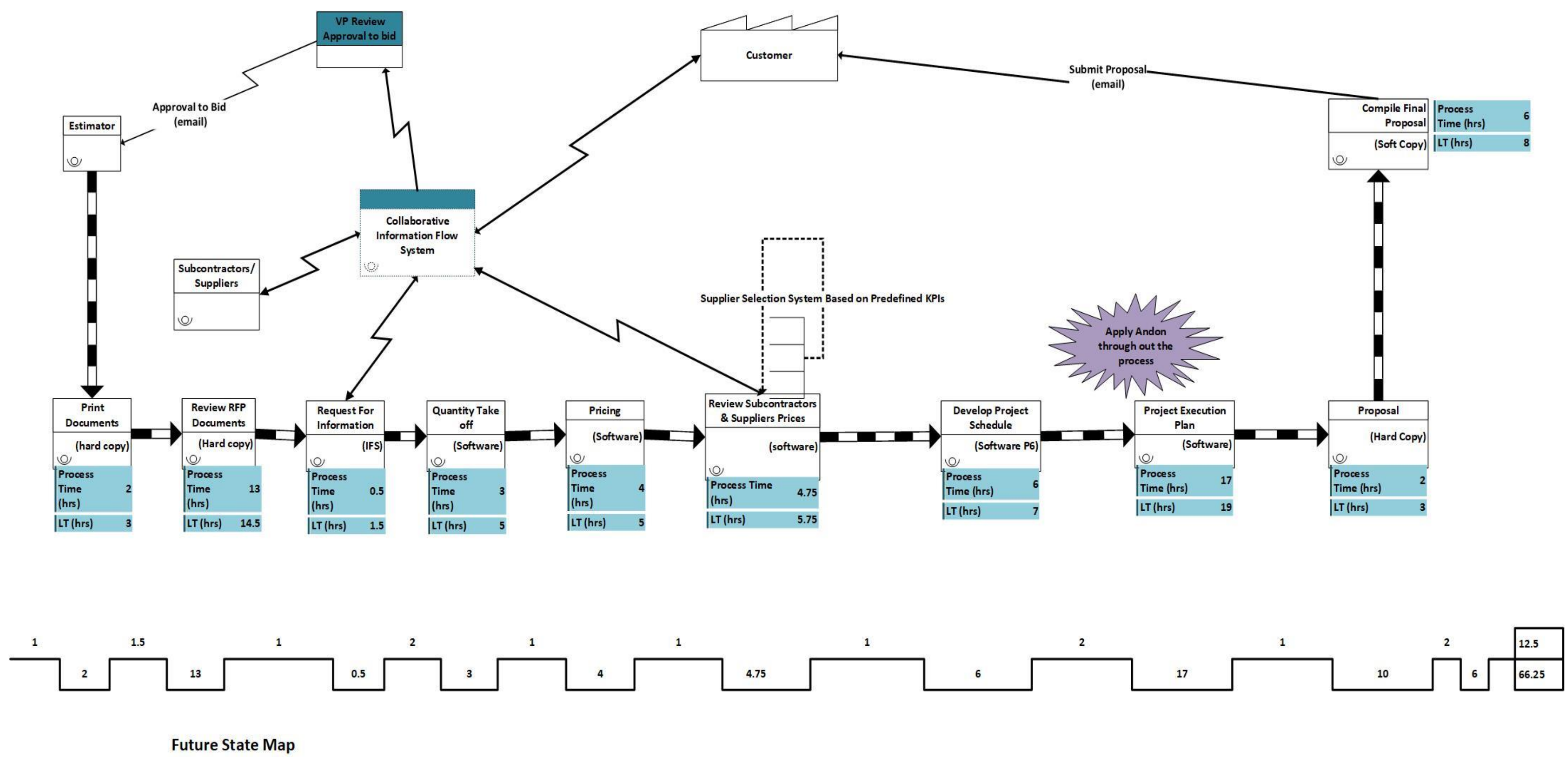
Appendices

Appendix A: Tender Case Study

Value stream mapping for tendering case study is completed. The current state VSM is shown in figure Appendix A- Figure 1. The process metrics are chosen processes and lead times, as well as information flow tools. The current state map shows the processing time is 86.25 hours, while the non-value-added time is 58.5 hours. The process has approximately 40% of the non-value-added time. The future state map is developed for the process and the processing time is reduced to 66.25 hours while the non-value-added time is reduced 12.5 hours by combing combining activities as well as applying Andon, i.e. estimators to ask questions once needed and eliminate the review activities as shown in figure Appendix A- Figure 2.



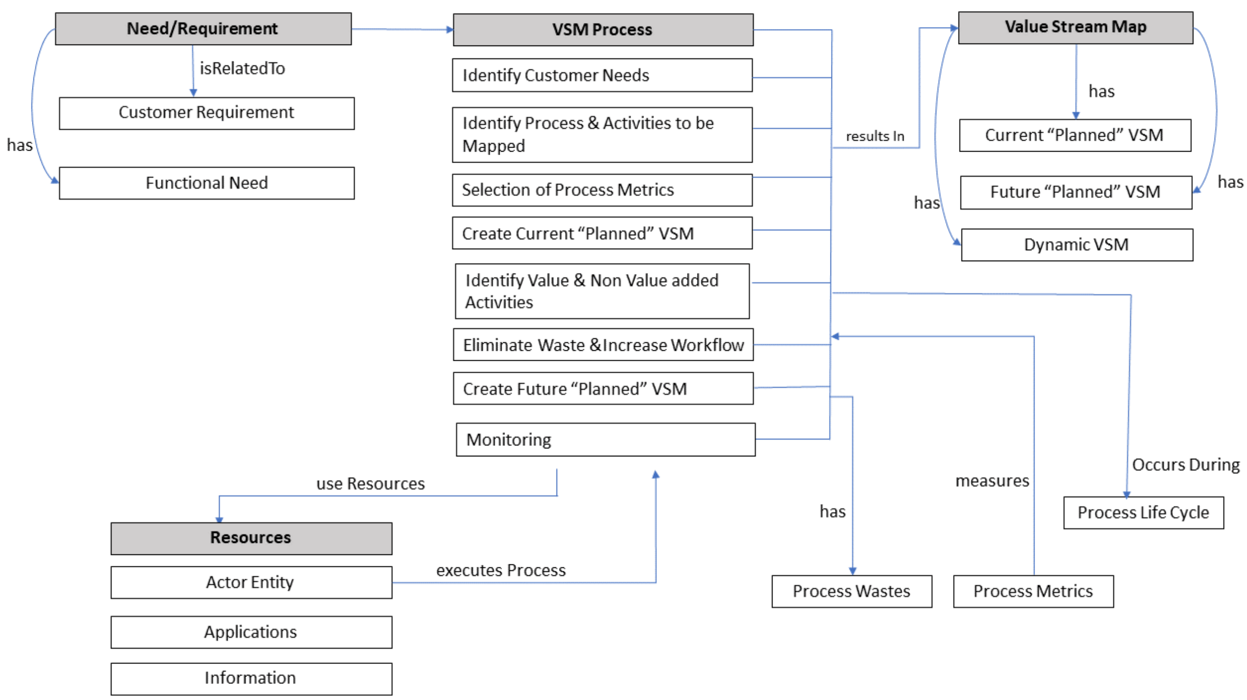
Appendix A- Figure 1: Current State VSM



Appendix A- Figure 2: Future State VSM

Appendix B: VSM Ontology Classes

The entities for the VSM model are arranged based on the Basic Formal Ontology (BFO) structure. The model is based on four major entities, which are customer requirements, processes, output (VSM) and resources, as shown in Appendix B- Figure 1. The customer needs and/or requirements initiates the VSM process that uses resources and results in current and future VSMs.The framework for developing and utilizing existing ontologies in manufacturing and design has been followed in this study [137] . Following are the steps we followed in



Appendix B- Figure 1: VSM Framework

developing the ontology:

***Step 1:** Specify the purpose and scope of the ontology*

The scope of the ontology is establishing a common understanding for VSM by structuring its knowledge to facilitate its application along with construction supply networks.

Step 2: *Categorize concepts and develop a class hierarchy*

BFO describes concepts in terms of continuants and occurrents. Continuants are entities that exist through time while occurrent is events or processes in which continuants participate [190]. Continuants have three major subclasses [113]:

(i) Independent continuants which represent entities that can exist by themselves such as objects. Material and immaterial entities are the two major subclasses for the independent continuants. In VSM ontology, physical resources such as actors, materials, equipment, etc. are represented as a subclass of the material entity, while non-physical resources such as software, applications are represented as a subclass of the immaterial entity.

(ii) Specifically dependent continuant which represents entities that depends on other entity to exist such as colour, mass, etc. In VSM ontology, process and activities qualities such as process metrices and wastes are represented as subclasses of specifically dependent continuant. These qualities measure and describe activities and processes, and their existence is dependent on the existence of associated activity or process.

(iii) Generically dependent continuant (GDC) which are entities that cannot exist unless other entity exists and are able to migrate from bearer to another such as pdf file. In VSM ontology, information is represented as a subclass for the GDC. Information needs a bearer to exist, and they can migrate from bearer to another.

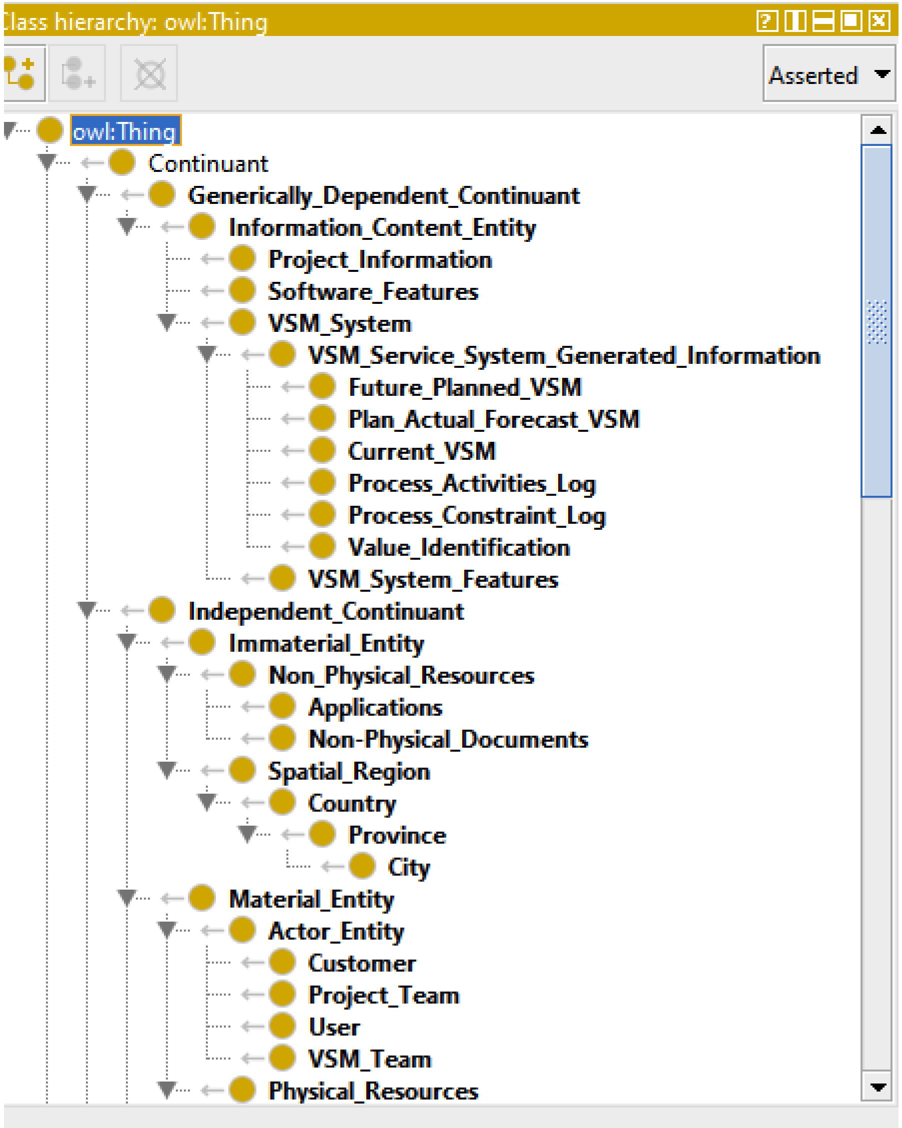
The second major entity for BFO is the occurrent which has two major entities [120]:

(1) Processes which are entities that exist in time by occurring or happening.

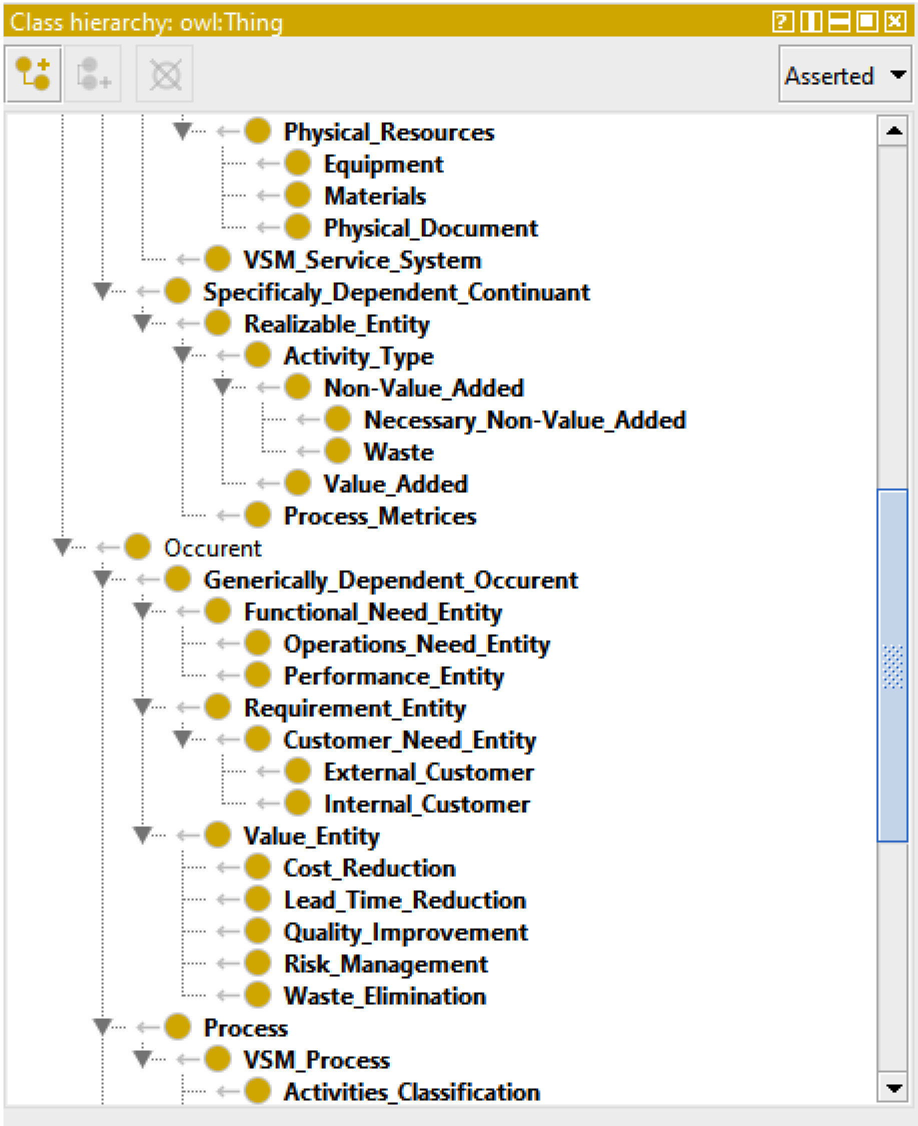
In VSM ontology, activities and steps to develop current and future VSMs are represented as subclasses of processes.

(2) Temporal region which are entities that are part of time. In VSM ontology, the timeframe for all entities is represented as a subclass for the temporal region.

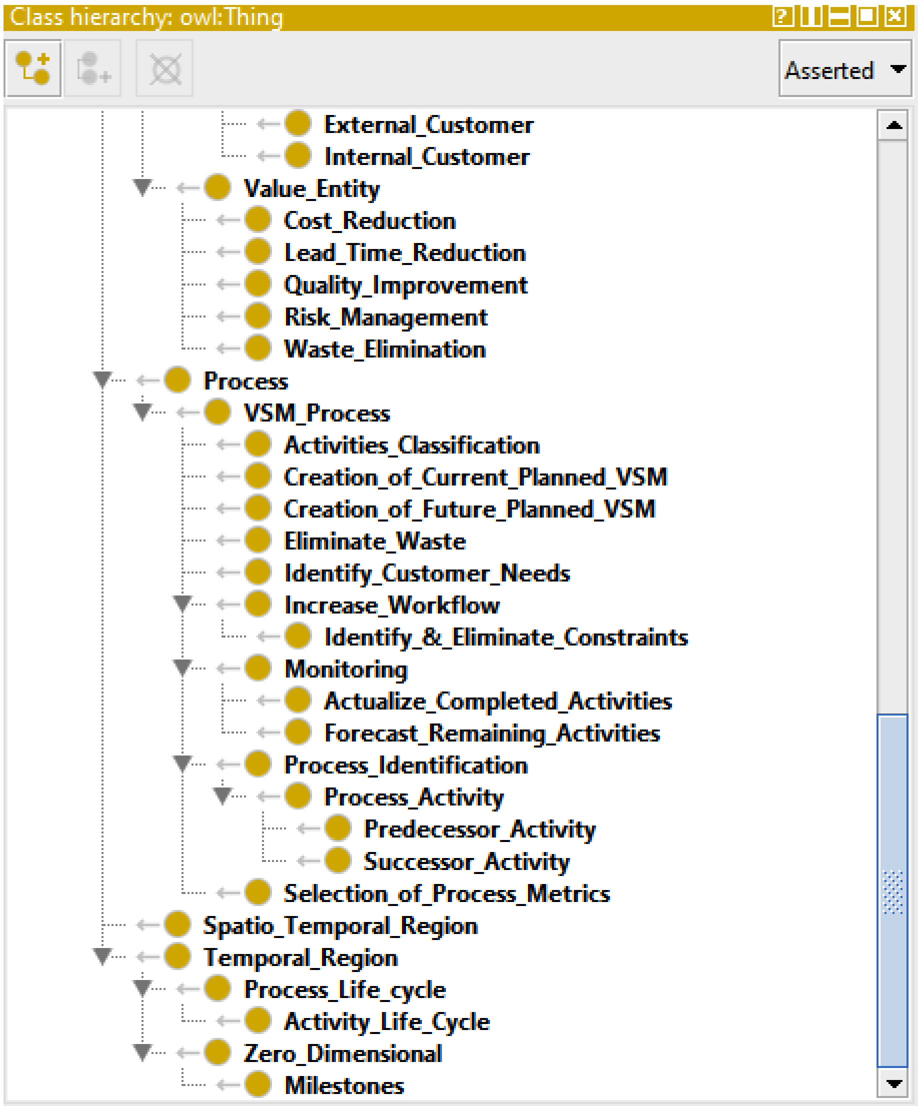
(3) Generically dependent occurrents are represented in VSM ontology as changes or events that occur and depend on the existence of other occurrences such as cost reduction, quality improvements, requirement and function entities. The ontology concepts are shown in Figures Appendix B- Figure 2, 3, and 4:



Appendix B- Figure 2: VSM Ontology Concept (protégé) (1of 3)



Appendix B- Figure 3: VSM Ontology Concept (protégé) (2 of 3)



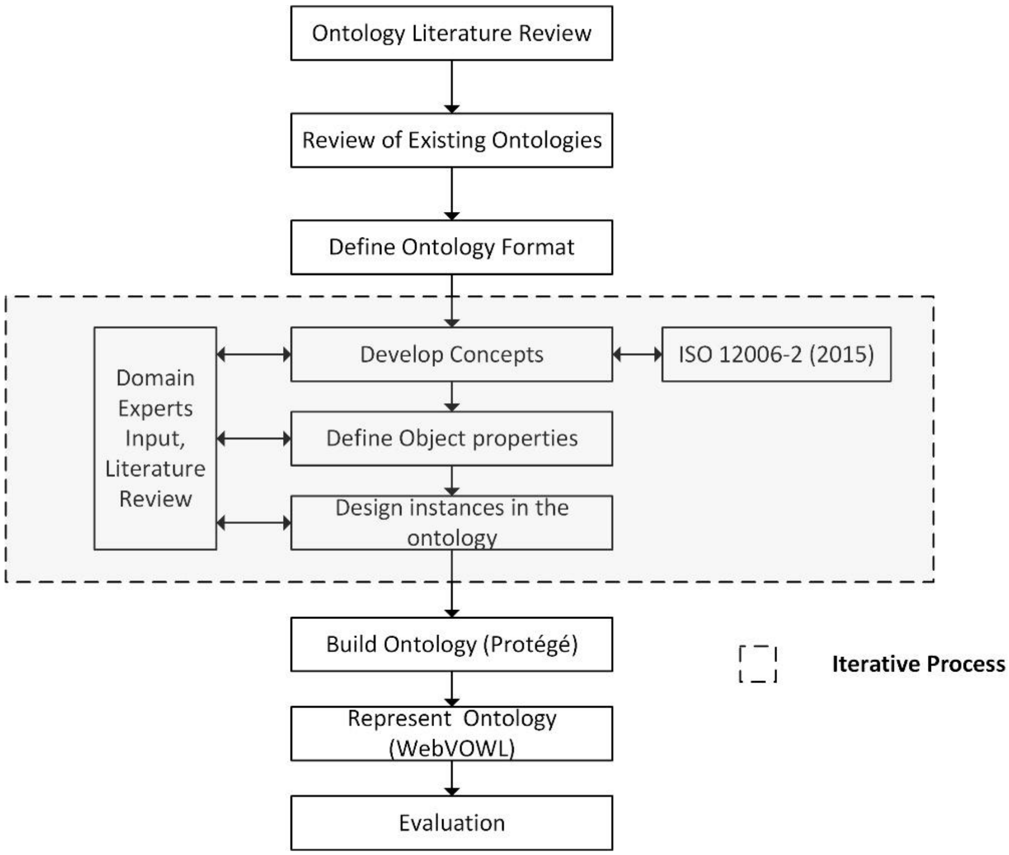
Appendix B- Figure 4: VSM Ontology Concept (protégé) (3 of 3)

Appendix C: Construction Knowledge Ontology

The ontology is developed using Basic Formal Ontology as an upper ontology, incorporating ISO 12006-2 recommendations and conducting interviews with domain experts, as shown in figure 1. Ontology's entities are arranged based on BFO structure, which is a formal ontology framework that was developed initially for natural sciences then extended to other domains [120]. BFO is a mature upper ontology [139] that has been used in developing hundreds of ontologies in various domains [133]. Therefore, developing construction ontology using the BFO structure can support its interoperability with other domain ontologies.

The developed framework follows ISO 12006-2 (2015) recommendations. ISO 12006-2 is an international standard that provides a basis for classifying construction systems. It also gives examples that explain the construction concepts so organizations can follow to develop their own classification systems [138]. Following ISO 12006-2 recommendations can facilitate adapting and standardizing the framework in the industry.

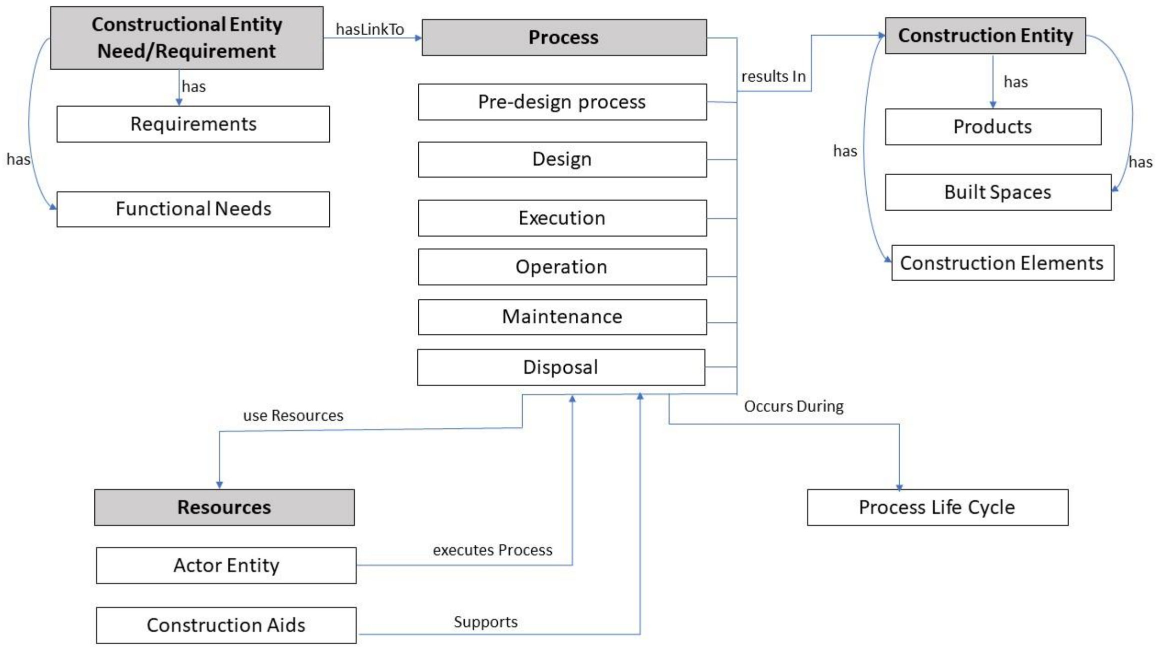
The ontology concepts, relationships and properties are developed via interviews with industry experts. Then Protégé is used to build the ontology and WebVOWL to represent it. Protégé is an open-source ontology editor and framework developed at Stanford University [205]. WebVOWL is an ontology visualization tool that aims to provide an intuitive and comprehensive representation that can be understood by users less familiar with ontologies [192]. The ontology is evaluated by using protege built in reasoner and competency questions answered by industry experts.



Appendix C- Figure 1: Construction Ontology Development Methodology

Construction project starts from a need to build a construction entity to fulfil a requirement such as living, producing, or manufacturing. The project should meet certain criteria such as financials, jurisdictional, social, and engineering that may act as guidelines and constraints for the project. The needs and requirements to build the entity initiate the processes, which include but not limited to pre-design, design, construction execution, operations, and disposal. The processes occur during a process life cycle which is the timeframe for the process and/or activity; the process uses resources such as construction aids, e.g. scaffolding and earth moving equipment, which is equipment and/or materials that support the processes, but they do not form a part of the construction entity. Actors such as engineers and construction professionals execute the processes that result in a construction entity that fulfills the owner's needs and requirements. The construction entity, e.g. a building, plant, and bridge, has products such as materials and equipment that form apart of it. It also has spaces and elements, which are a group of materials and/or equipment that form a system such as a wall and HVAC systems. A summary of the ontology framework is shown in Appendix C- Figure 2. The scope of the ontology is to structure construction knowledge from the early project's phases to the final one to streamline information flow and support data integration with other domains.

Formal and upper ontologies facilitate communication among domain ontologies, which supports the interoperability and integration of these ontologies. Therefore, following the BFO structure supports the integration of the developed ontology with other domain ones. ISO 12006-2 (2015) recommendations are followed, which promotes the standardization of the concepts. Six interviews with domain experts are conducted to have their inputs in developing the ontology. The BFO is presented to the interviewees, so they understand the structure and the purpose of the ontology. Then the subclasses and their relationships are developed using their inputs.



Appendix C- Figure 2: Construction Knowledge Ontology Framework

BFO is based on fundamental distinct between continuants and occurrences. Continuants are entities that exist through time while occurrent is events or processes in which continuants participate [190]. Continuants have three major subclasses [113]:

(iv) Independent Continuants represent entities that can exist by themselves, such as objects. Material and immaterial entities are the two significant subclasses for the independent continuants:

- Material Entities are independent continuants that have three dimensions and continues through an interval of time. In the developed ontology, the material entity has three significant subclasses. The first one is construction entities, which result from the execution process such as buildings, plants, facilities. Buildings, industrial and infrastructure entities are the subclasses of construction entities that represent construction sectors. The second subclass of material entity is the construction resources, which represent materials, equipment, tools and actors that participate in processes. The third subclass is the object aggregate, which is group of products that form a system. Construction element entity such as wall and HVAC system is the major subclass for the aggregate object entity.

- Immaterial Entities are independent continuants that have no material entities as parts. Continuant flat boundary and spatial region are the main subclasses for the immaterial entity. Continuant flat boundary represents the boundaries and zones for material entities where the processes take place, which can change as materials move. However, the spatial region is fixed and represents the location of entities such as countries and cities. Software is another subclass for the immaterial entity.

(v) Specifically, Dependent Continuant (SDC) represents entities that depend on other entities to exist, such as colour, mass. SDC has two main subclasses:

- A quality which describes the internal and external properties for independent continuants such as mass and colour respectively. The quality status is a subclass for the quality entity which represents the conformance of material entities with design and standards. Relational quality is another subclass for the quality entity describes the relationship among entities which may vary based on projects such as contractual relationship.
- Realizable Entity, which describes the functions and roles for the independent continuants that are realized through associated processes such as the function of construction entity, is storing material or living use.

(vi) Generically Dependent Continuant (GDC) are entities that cannot exist unless another entity exists and able to migrate from bearer to another such as pdf file. In construction ontology, information is represented as a subclass of GDC. The information entity has subclasses that represent general industry information such as standards, codes and project-specific information that result from the project's processes.

The second major entity for BFO is the occurrent which has four major entities [120]:

i- Processes are entities that exist in time by occurring or happening. The processes for a construction process are classified based on the project phases. Processes have sub-processes that can be broken into activities. Following are the subclasses for the process entity:

- Predesign includes all activities and processes that occur before the design phase, such as project shaping, business case development.

  Project sanction usually takes place at the end of this process.

- Design Process includes engineering and architectural processes and results in design drawings and specifications that are issued for construction.
- Execution includes procurement, installation and commissioning processes, which result in a construction entity.
- Operation is the use phase of the construction entity, e.g. using it for living in a building project or production in a manufacturing facility.
- Maintenance is the process that ensures the construction facility is operating as per the design and within acceptable limits.
- Decommissioning is the process that shuts down the construction entity from operation status.

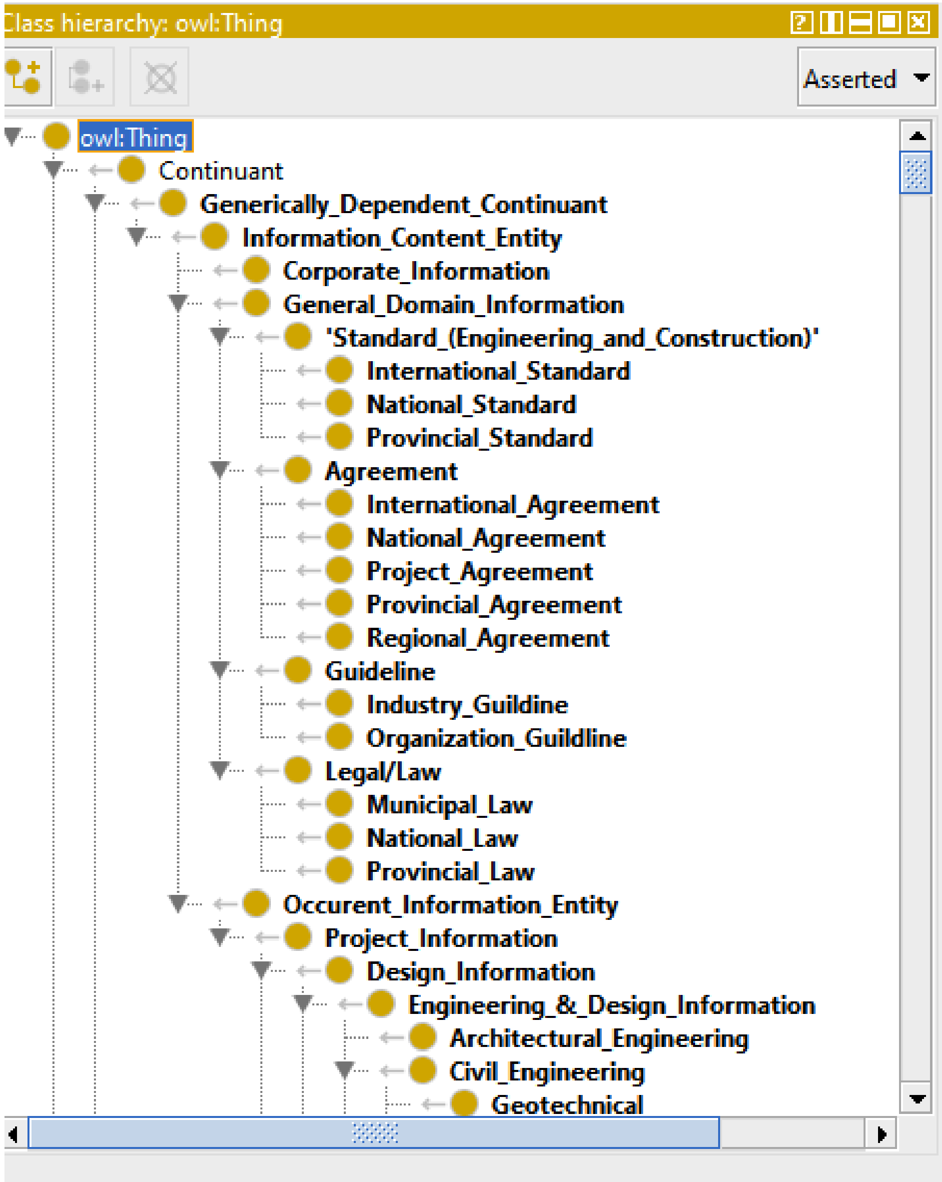
- Disposal is the process of removing the construction entity and then reinstate the zone as required.

ii- Process Boundaries are occurrents, and their existence depends on the existence of the process. They form the boundaries that the process should operate within, such as customer requirements, functional needs, and legislation requirements.

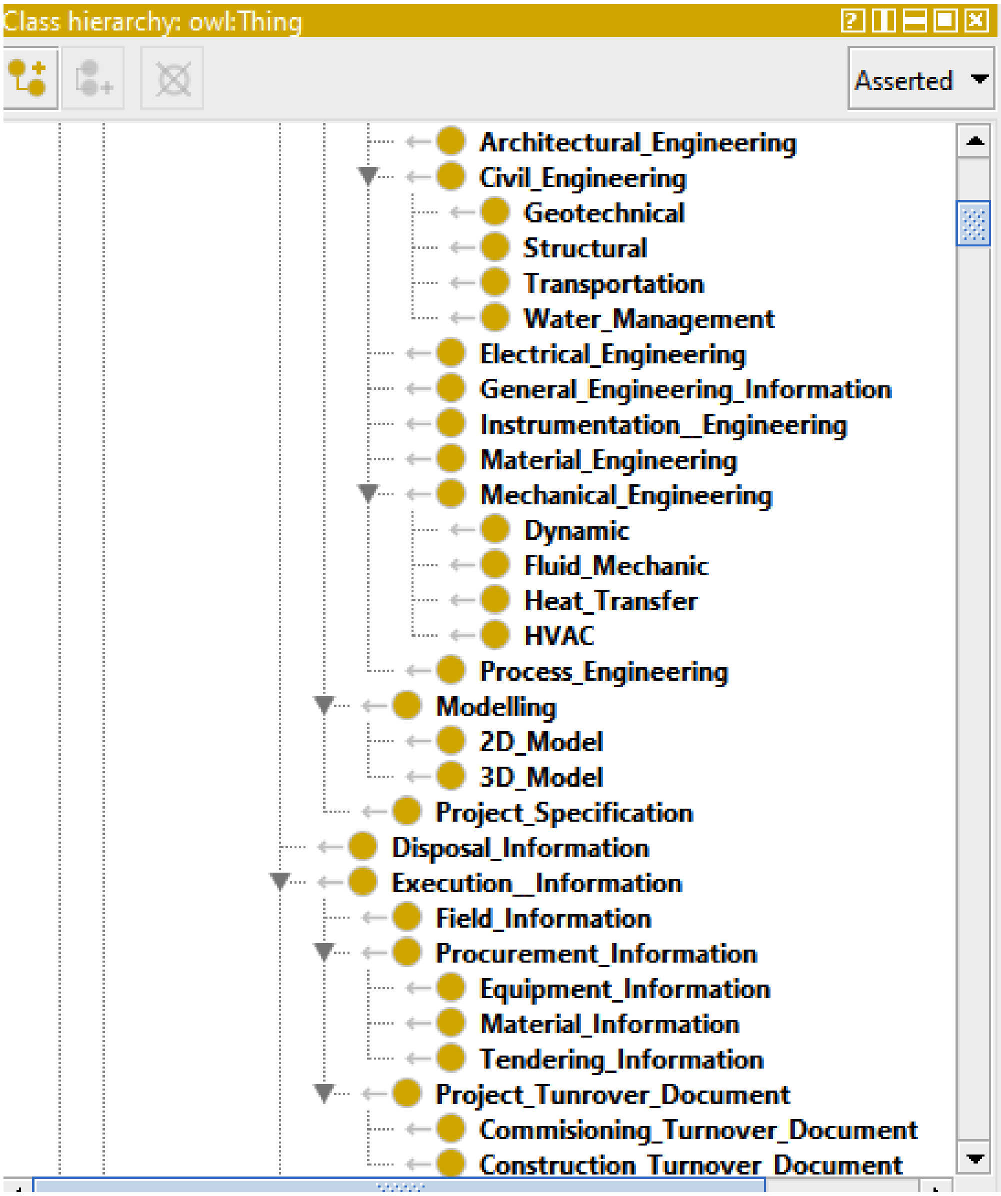
iii- Spatiotemporal region is a part of spacetime, e.g. the spacetime for a process that has a beginning, an end and a duration.

iv- The temporal region represents the temporal region of the spatiotemporal region, i.e. the timeframe for a process. The temporal region has zero- and one-dimensional temporal regions as subclasses. The zero-dimensional temporal region represents an instant in time, such as a start or an end of a process or activity, while the one dimensional temporal regional represents an interval of time in which a process occurs. The life cycles for processes are represented as subclasses of the zero-dimensional region.

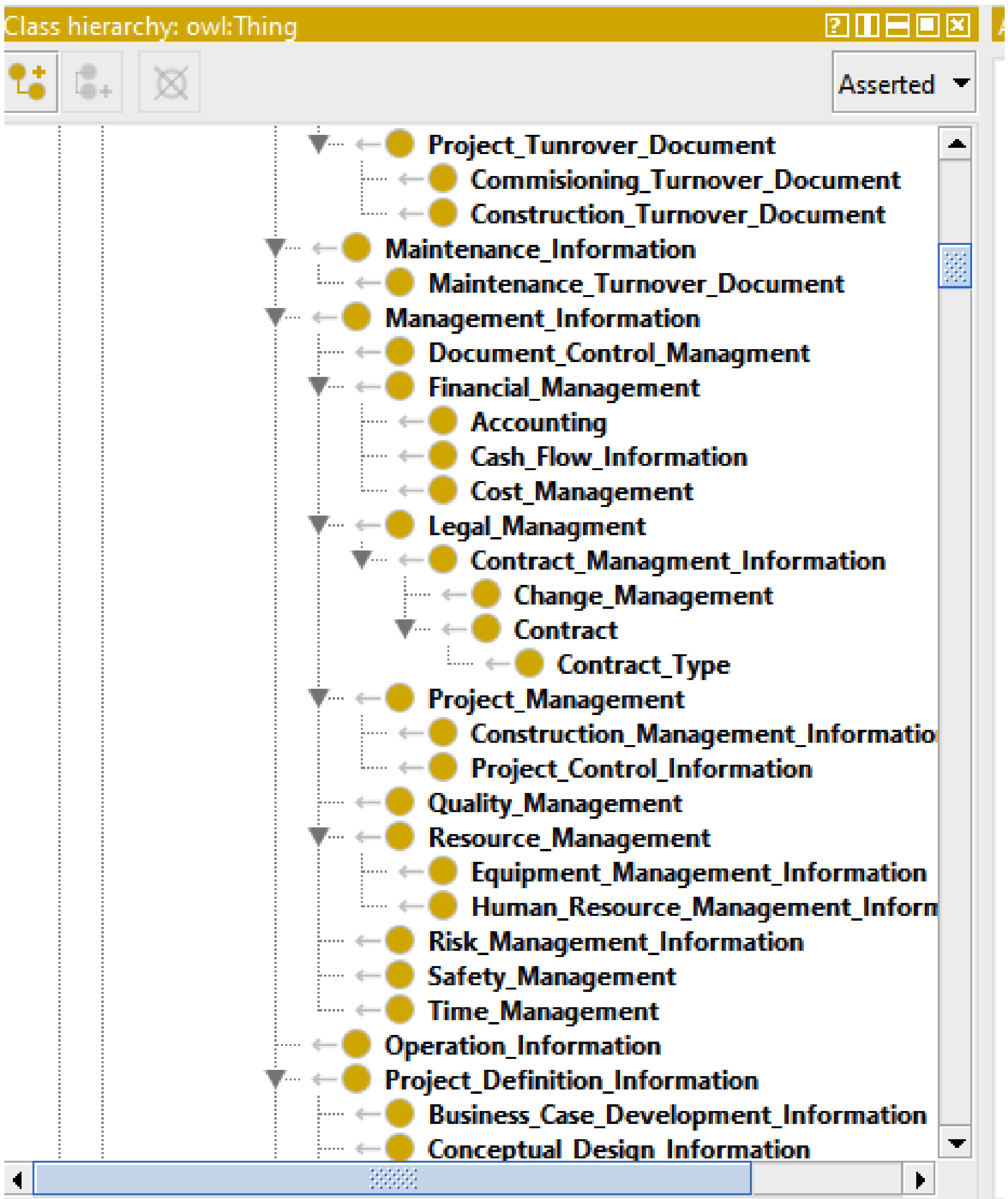
The concepts of the developed ontology are shown in Figures Appendix C- 3 to 21:



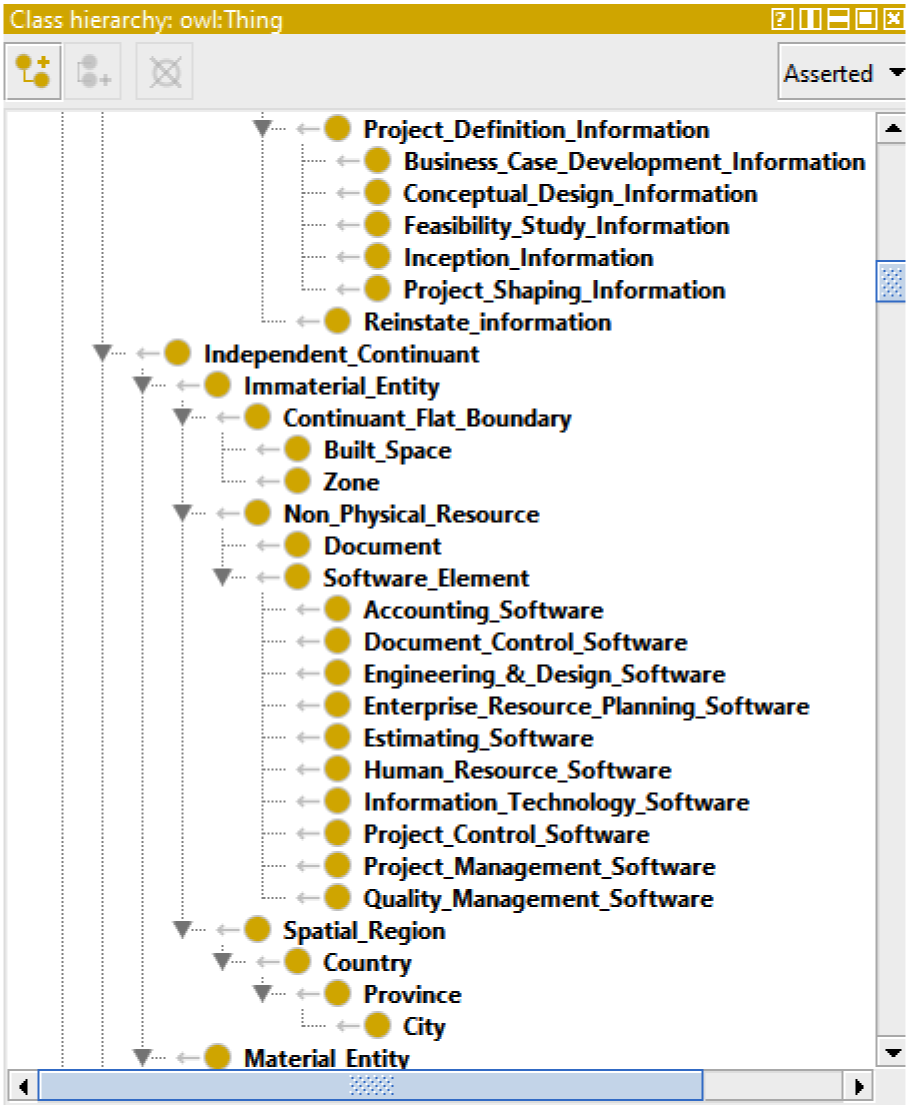
Appendix C- Figure 3: Construction Ontology Concepts (protégé) (1 of 21)



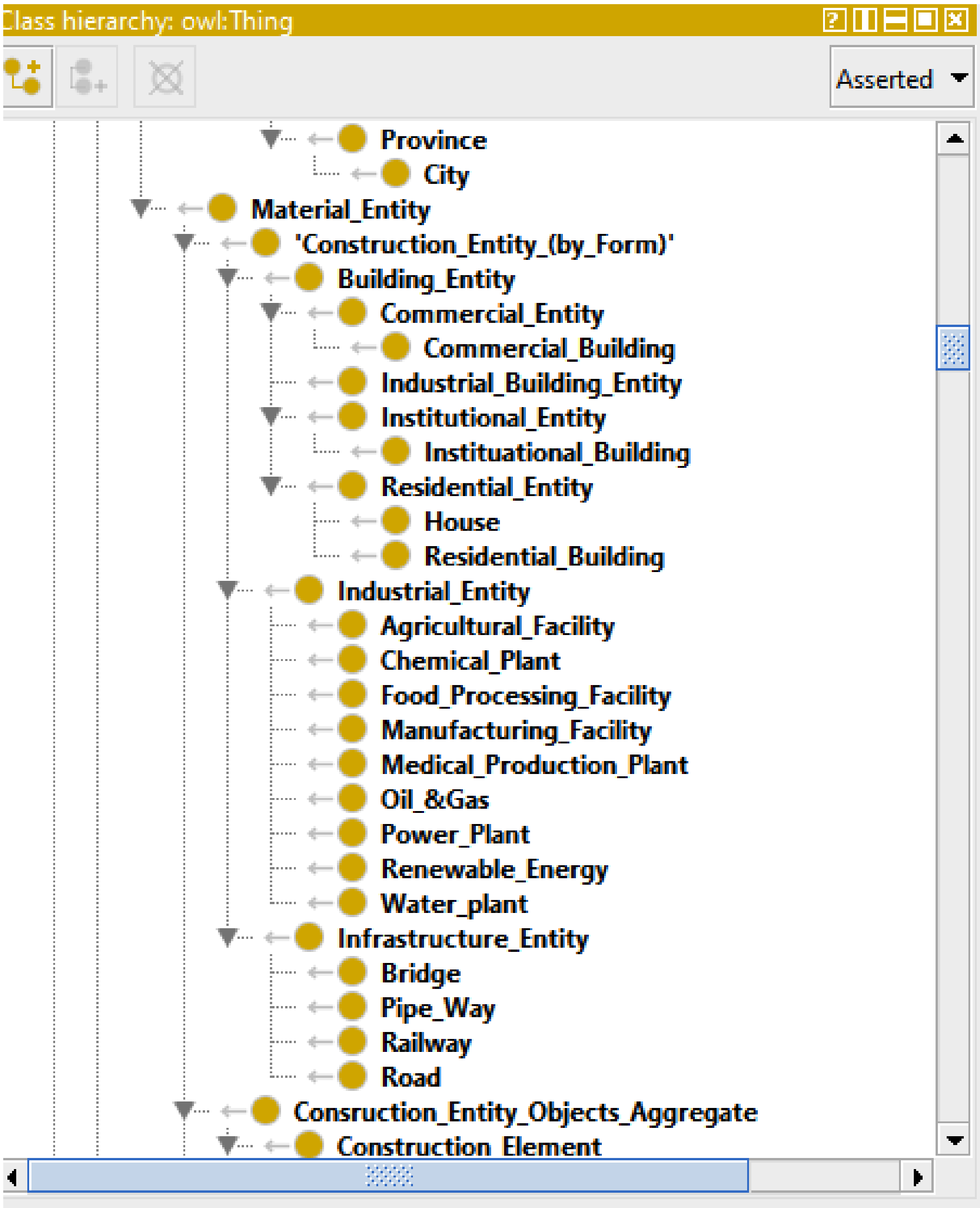
Appendix C- Figure 4: Construction Ontology Concepts (protégé) (2 of 21)



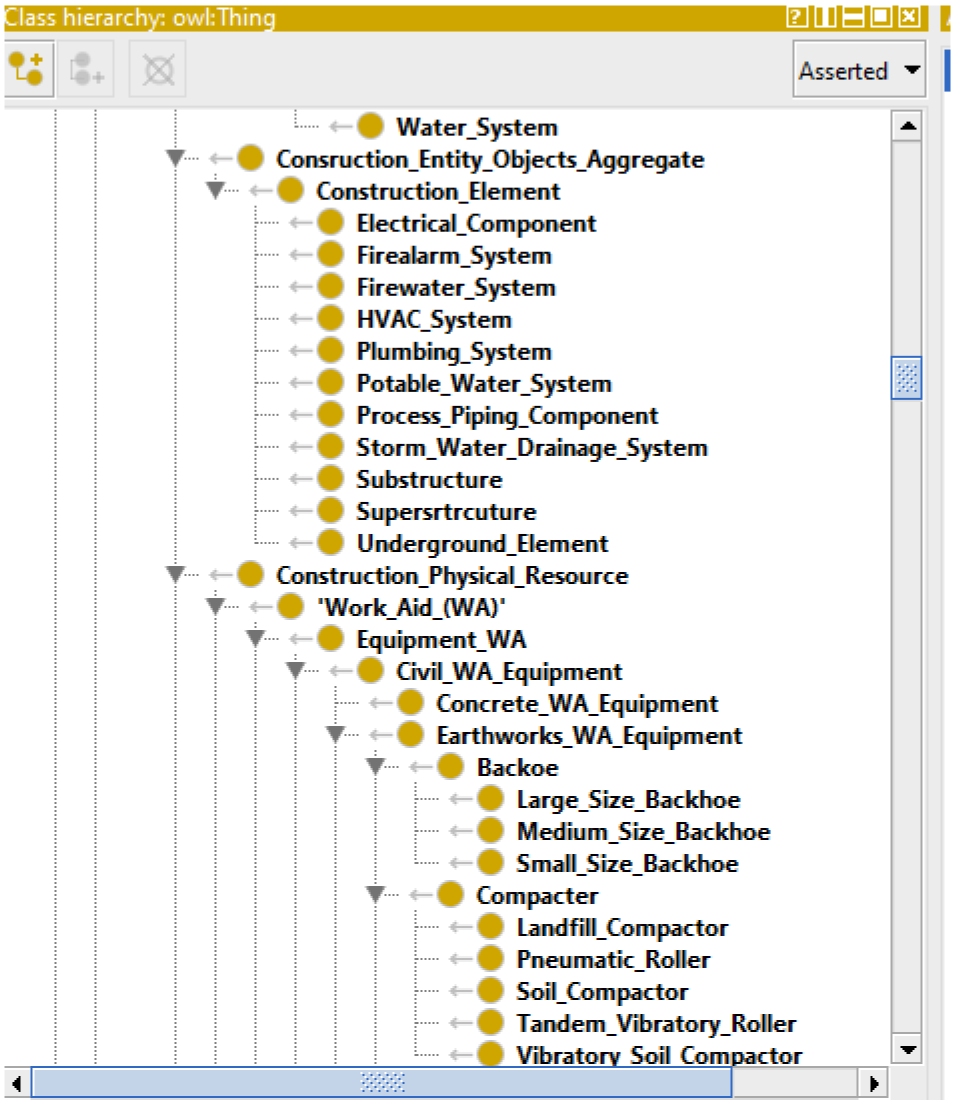
Appendix C- Figure 5: Construction Ontology Concepts (protégé) (3 of 21)



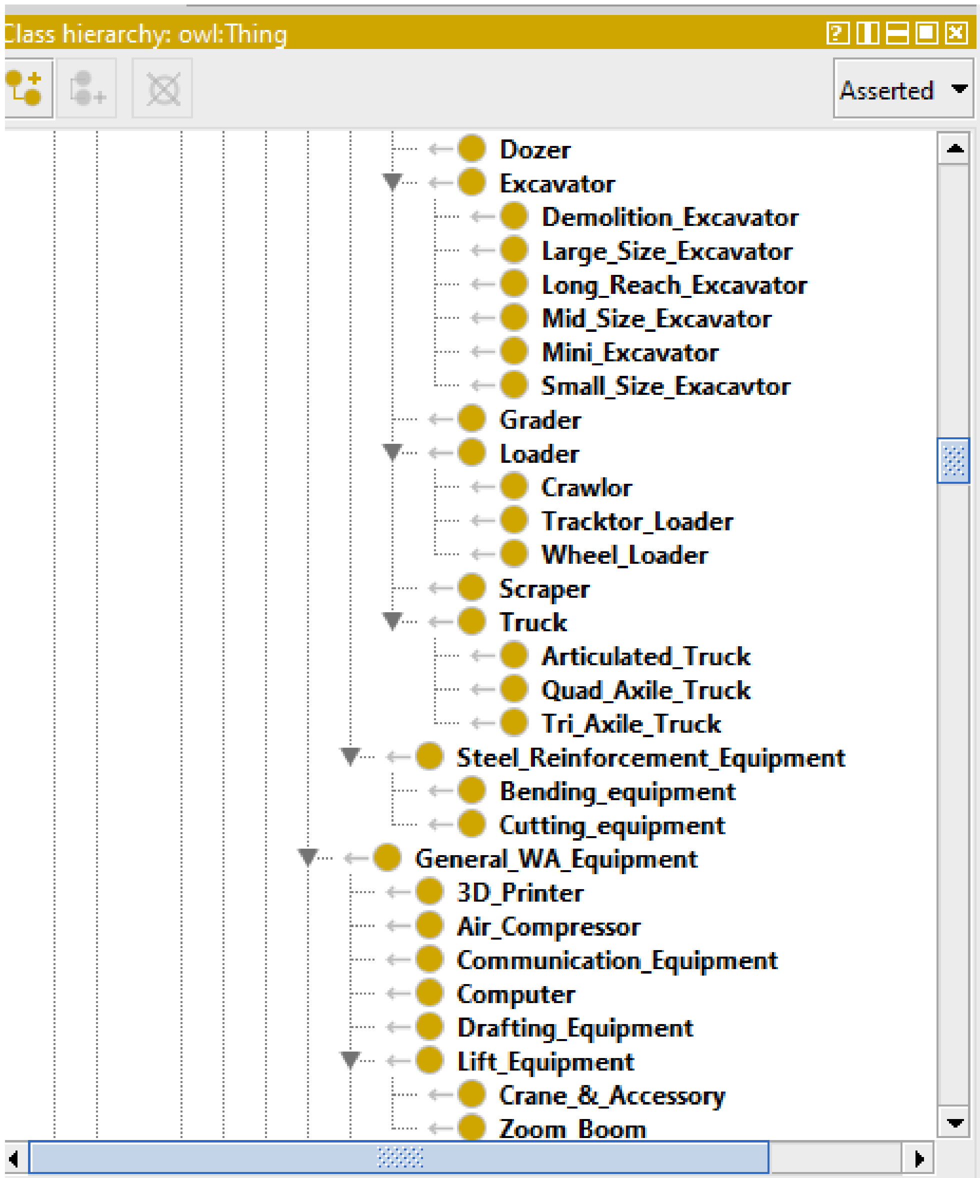
Appendix C- Figure 6: Construction Ontology Concepts (protégé) (4 of 21)



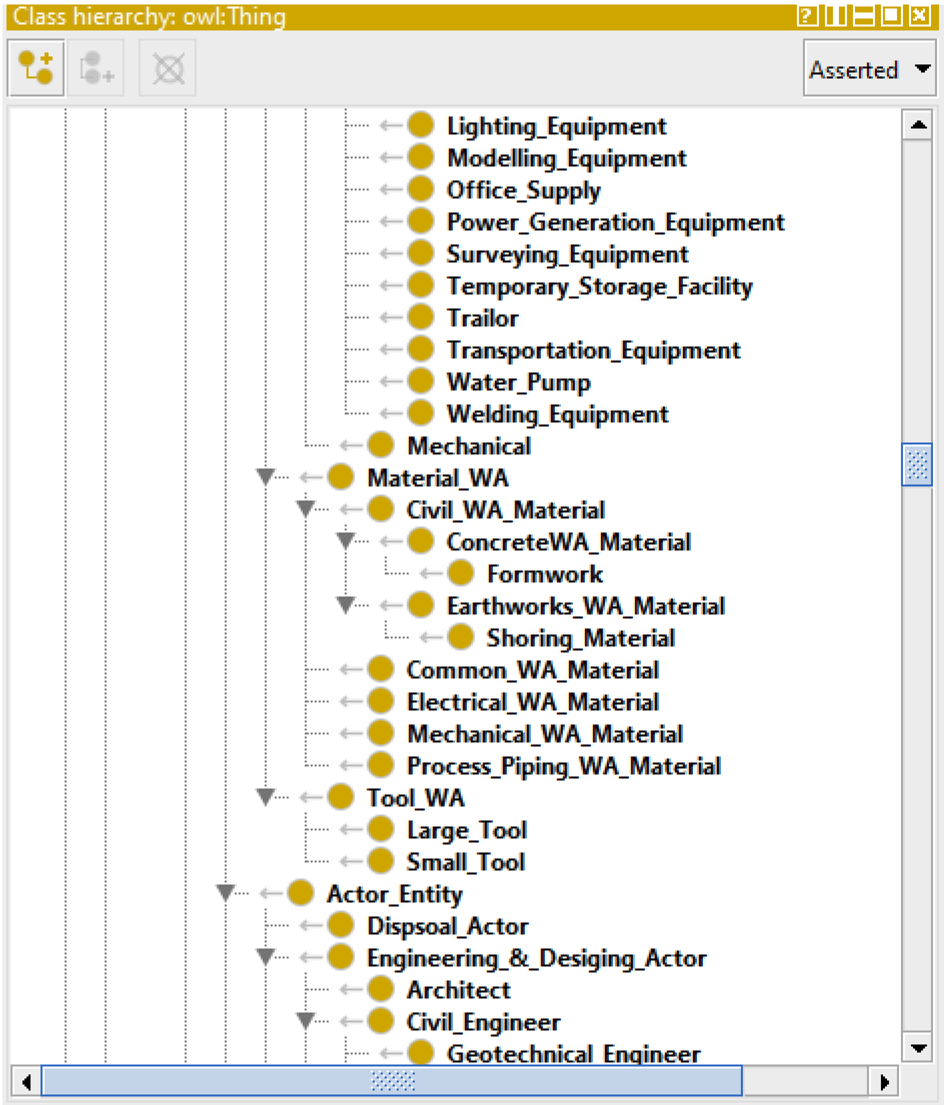
Appendix C- Figure 7: Construction Ontology Concepts (protégé) (5 of 21)



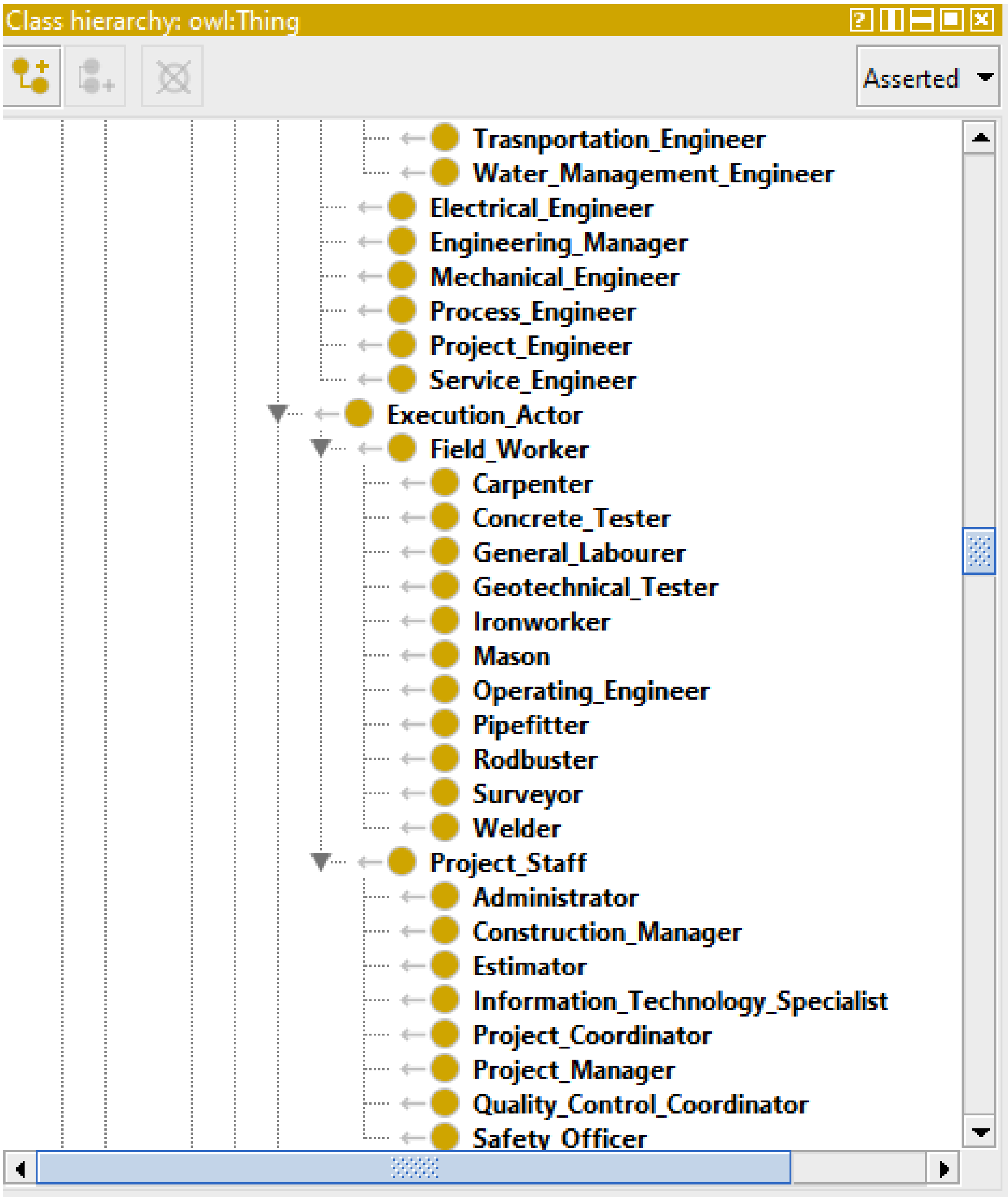
Appendix C- Figure 8: Construction Ontology Concepts (protégé) (6 of 21)



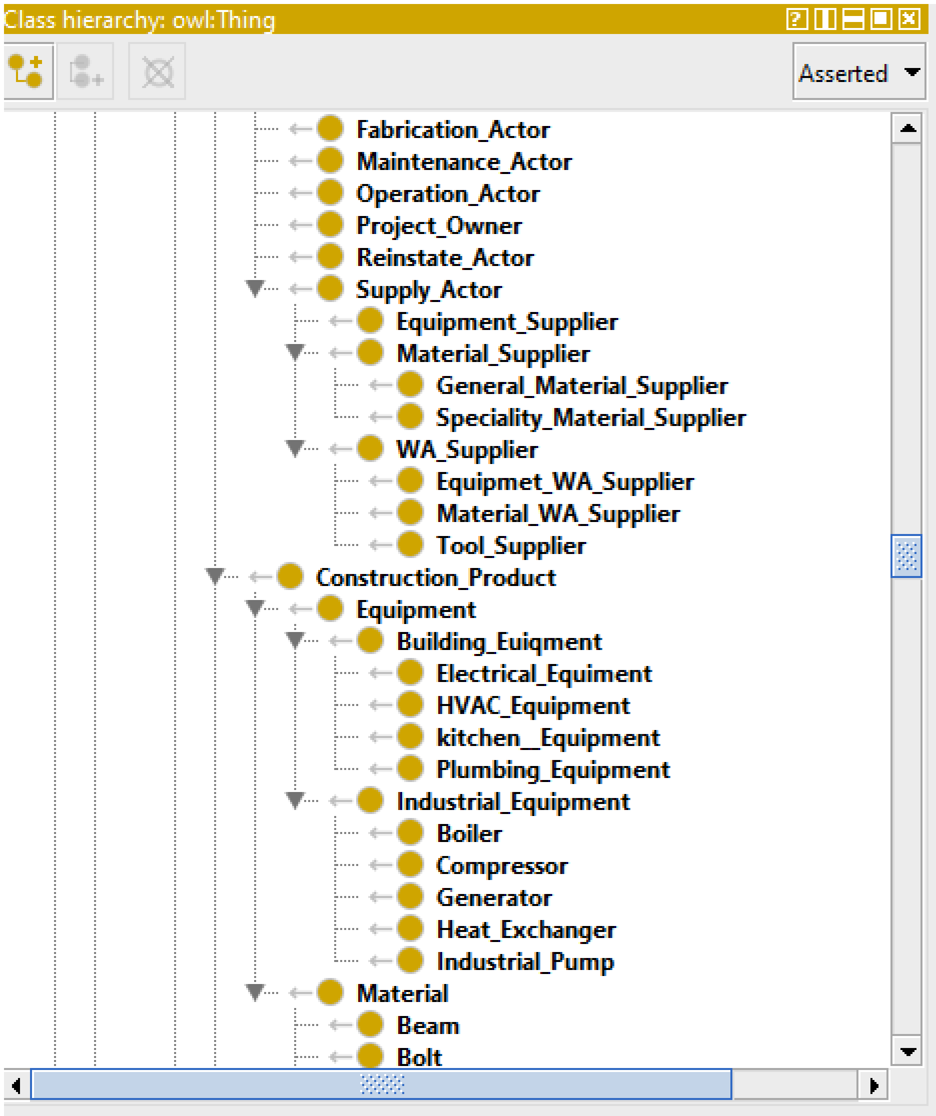
Appendix C- Figure 9: Construction Ontology Concepts (protégé) (7 of 21)



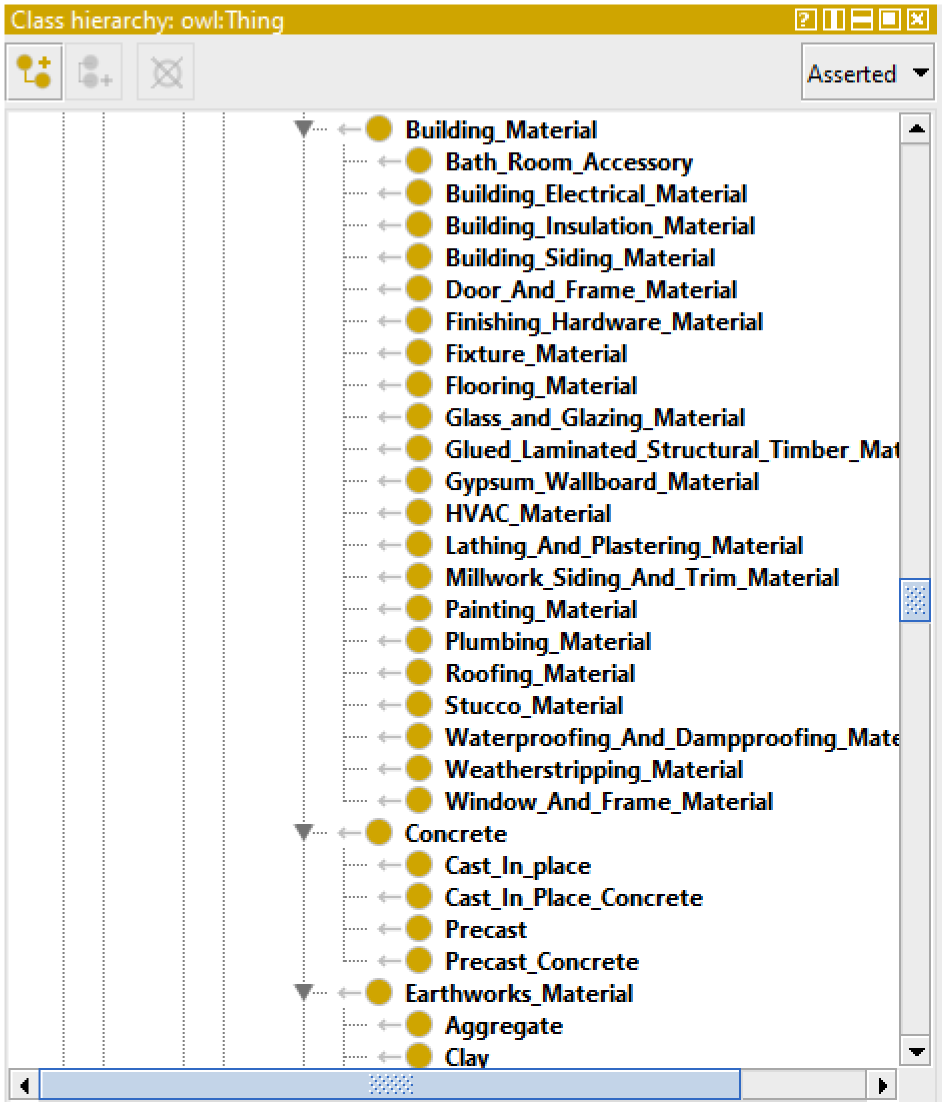
Appendix C- Figure 10: Construction Ontology Concepts (protégé) (8 of 21)



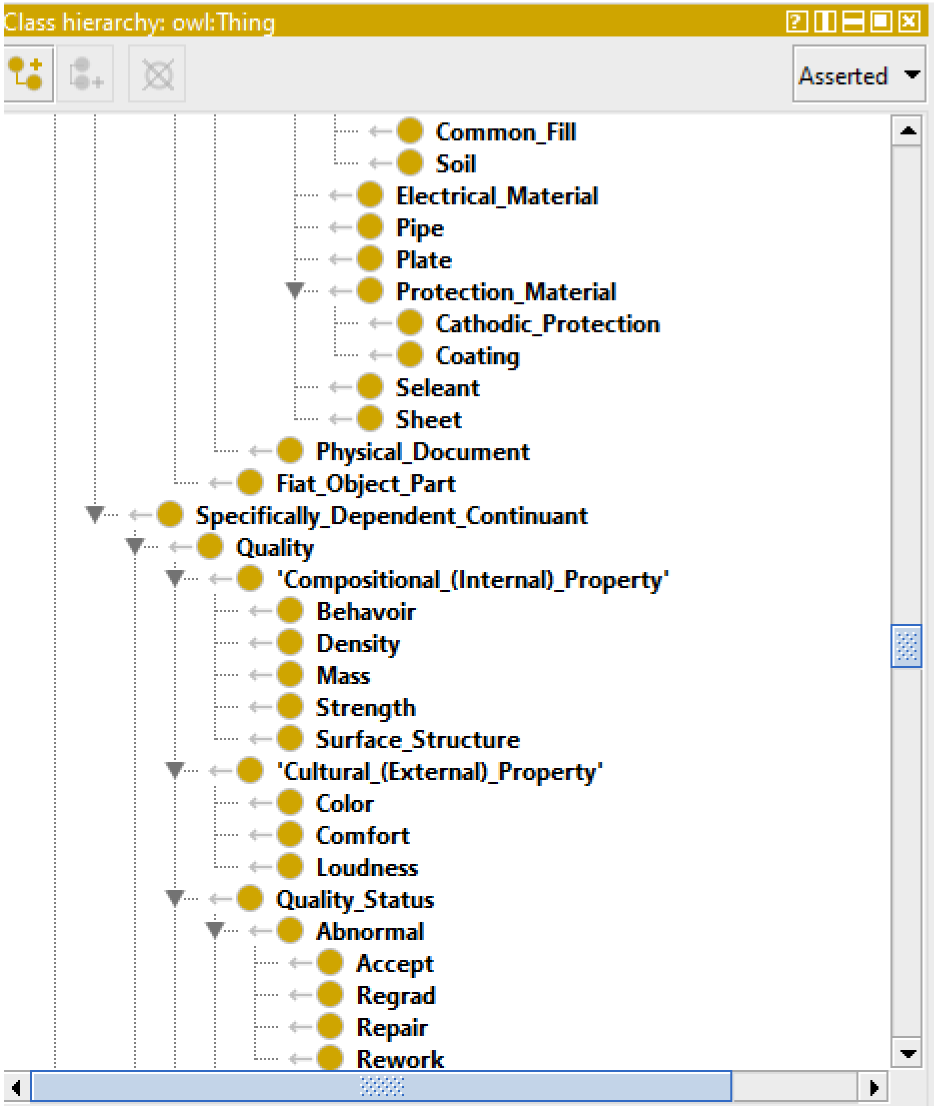
Appendix C- Figure 11: Construction Ontology Concepts (protégé) (9 of 21)



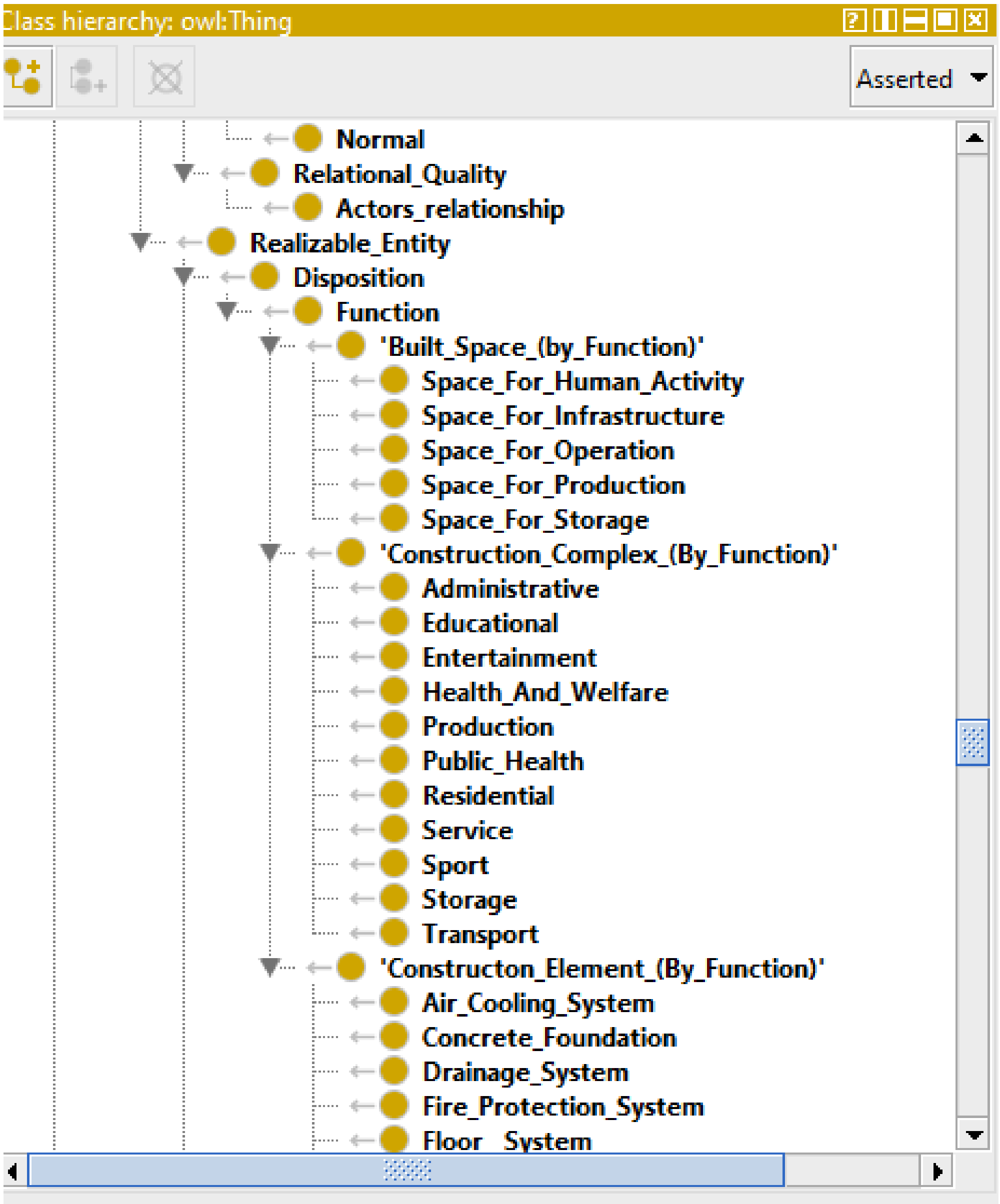
Appendix C- Figure 12: Construction Ontology Concepts (protégé) (10 of 21)



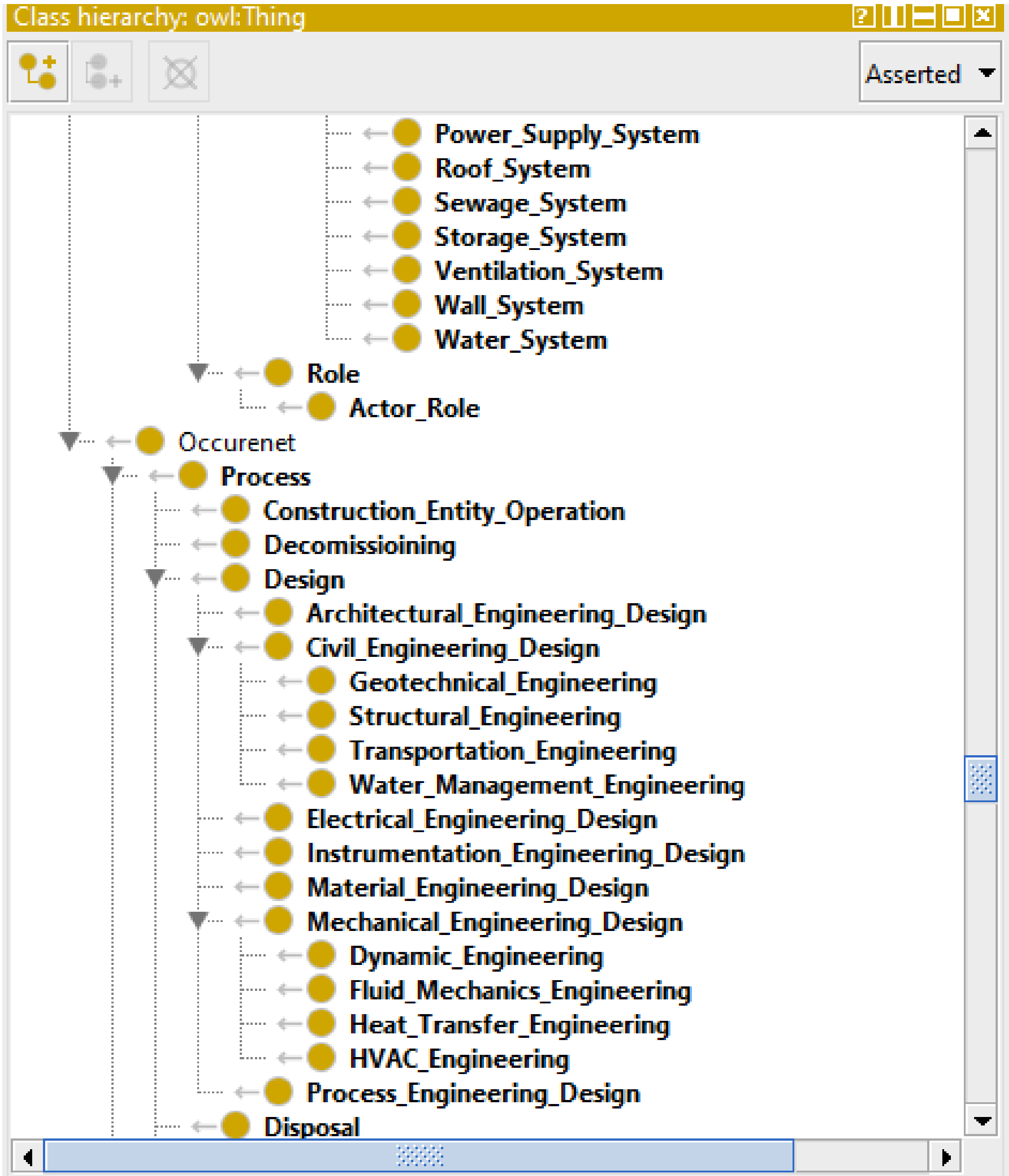
Appendix C- Figure 13: Construction Ontology Concepts (protégé) (11 of 21)



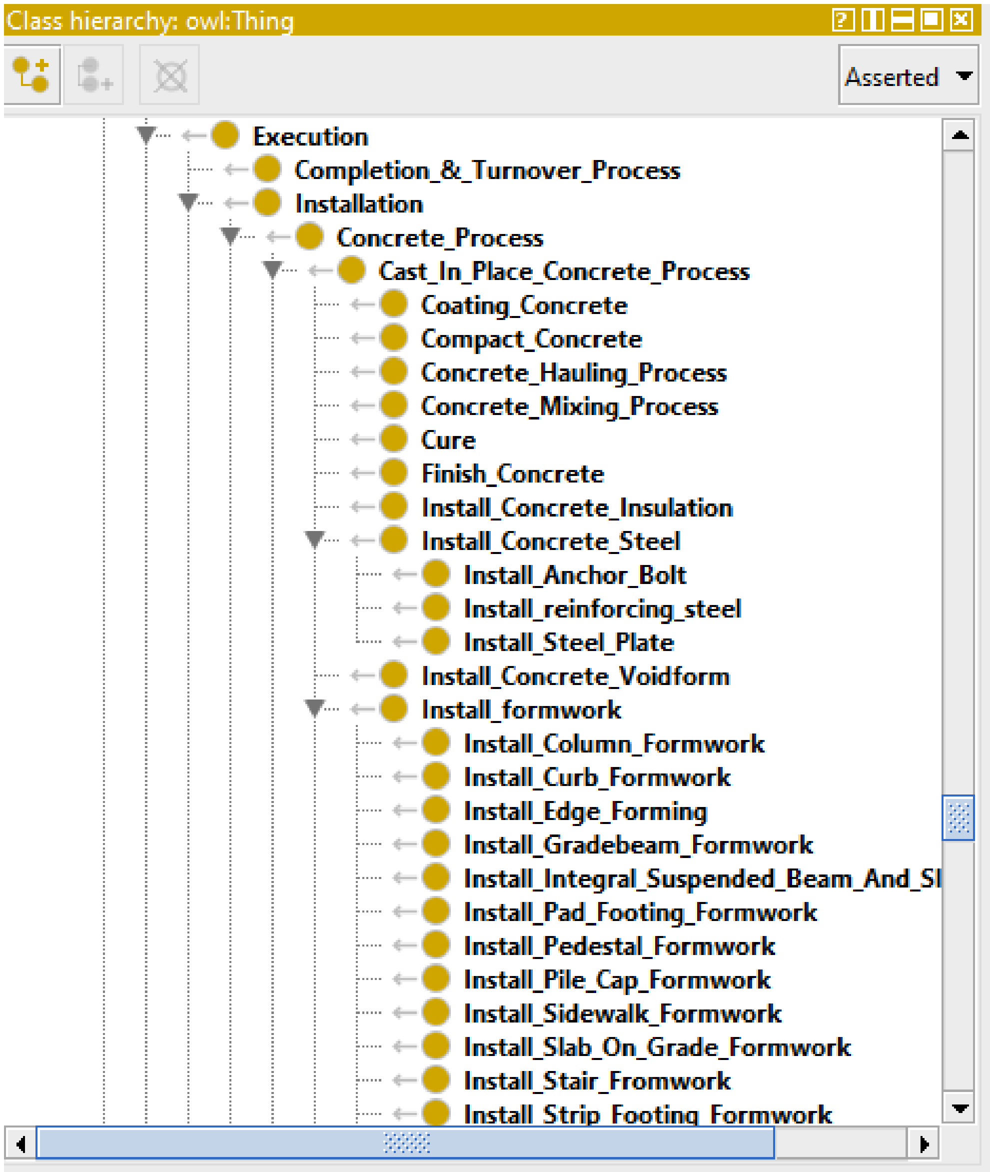
Appendix C- Figure 14: Construction Ontology Concepts (protégé) (12 of 21)



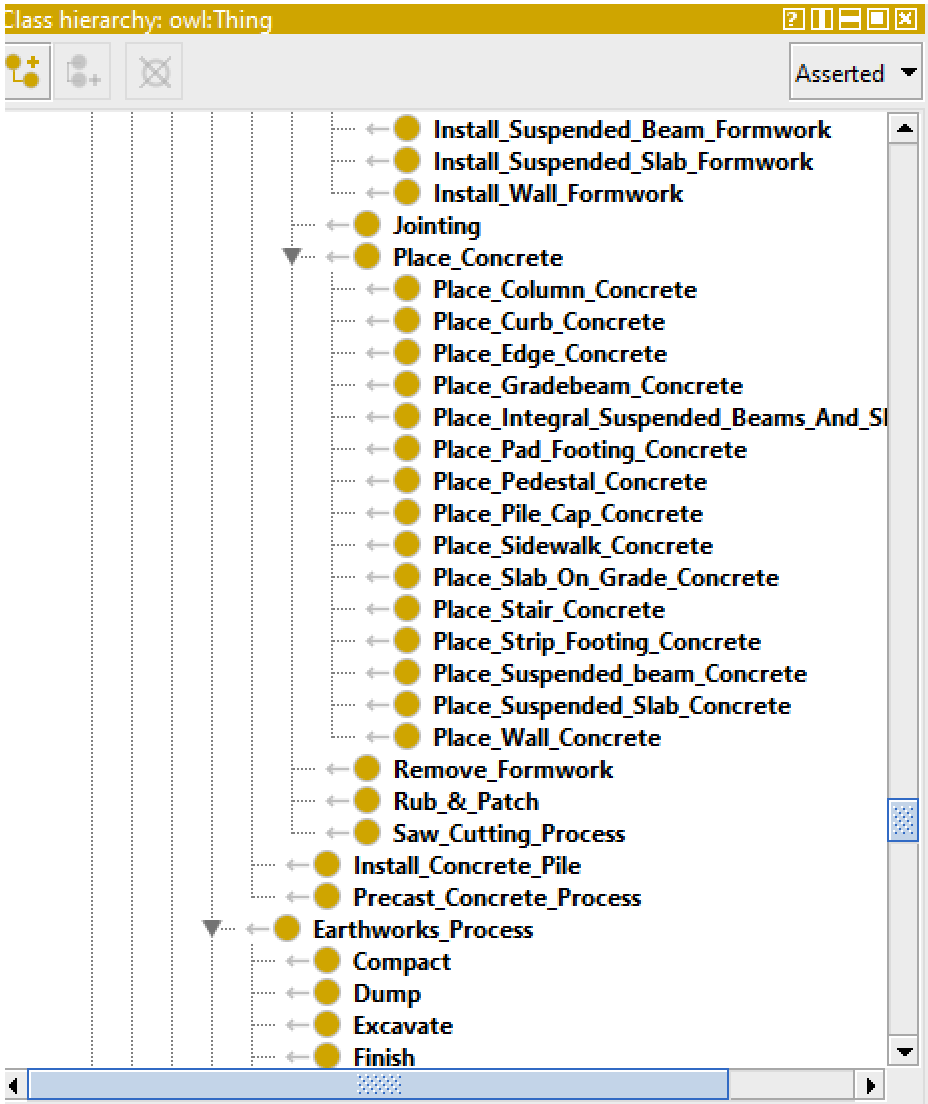
Appendix C- Figure 15: Construction Ontology Concepts (protégé) (13 of 21)



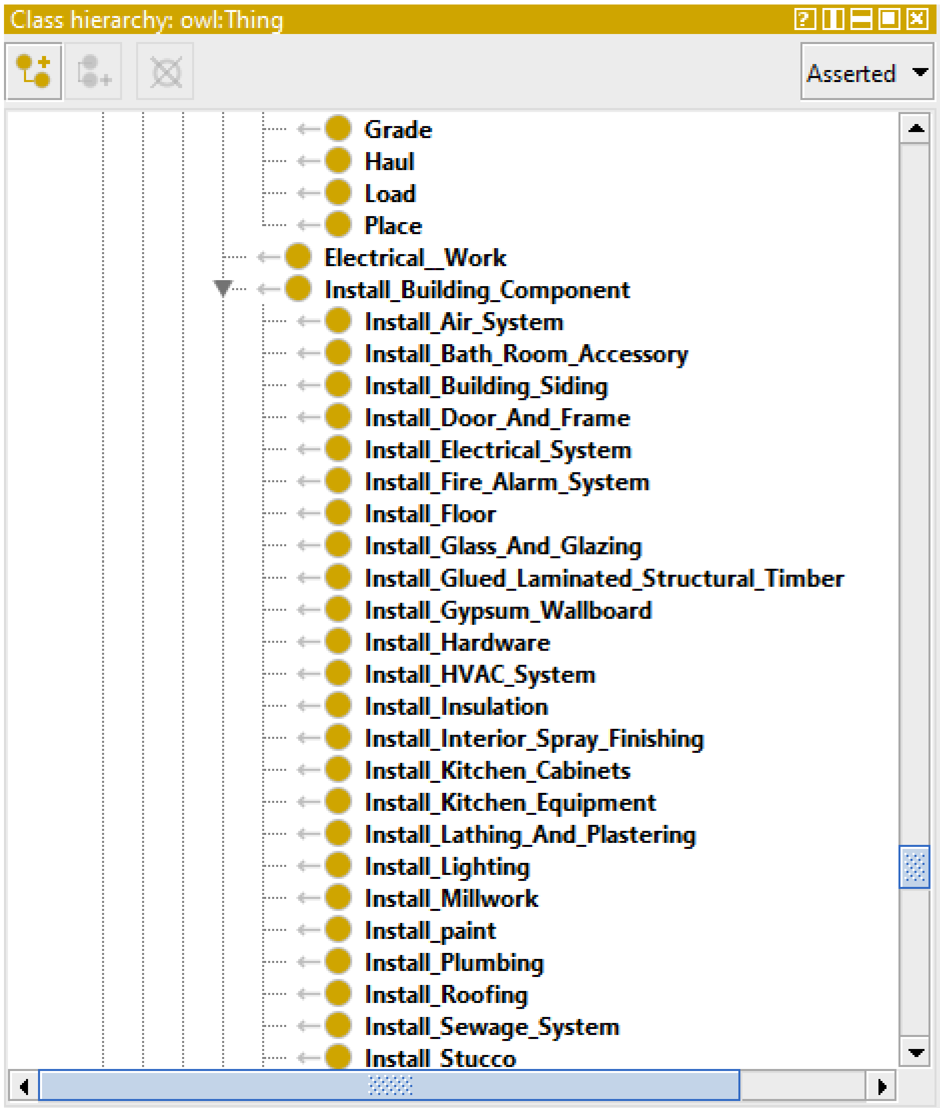
Appendix C- Figure 16: Construction Ontology Concepts (protégé) (14 of 21)



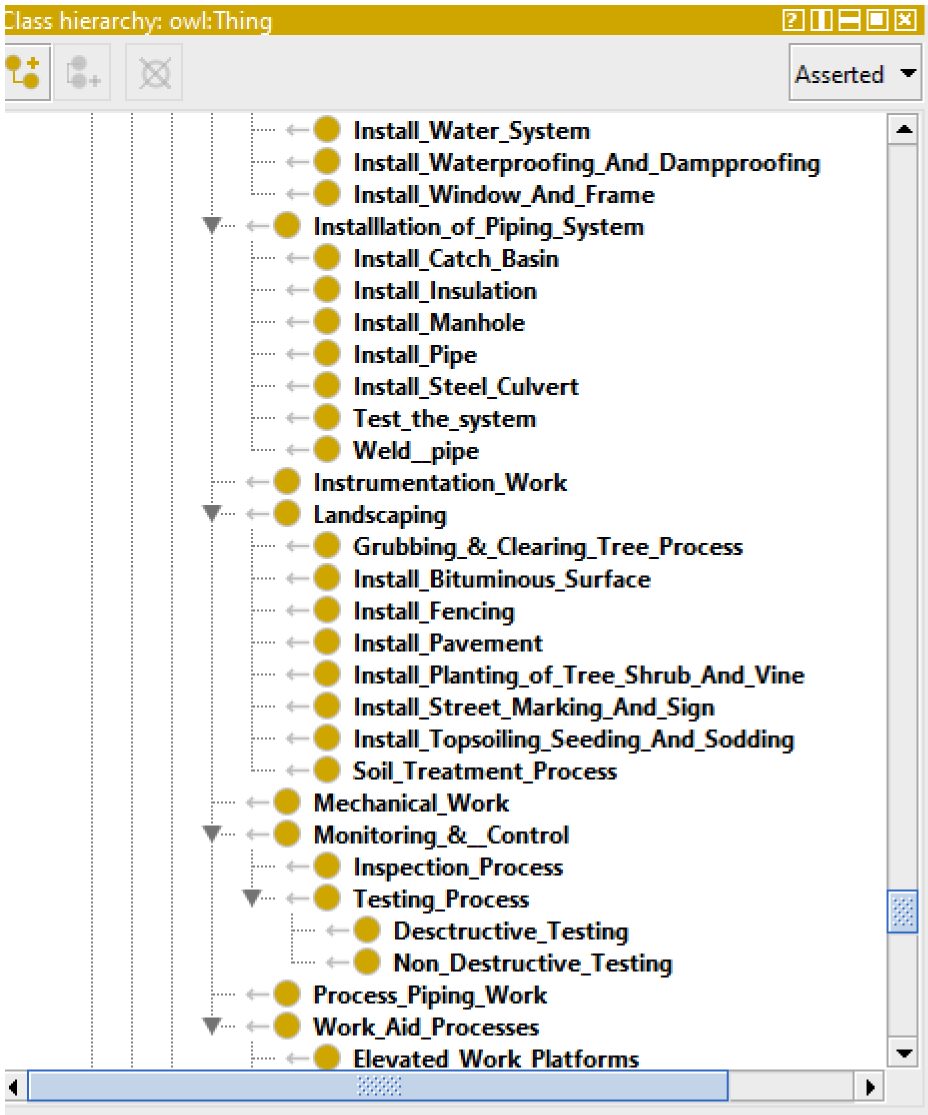
Appendix C- Figure 17: Construction Ontology Concepts (protégé) (15 of 21)



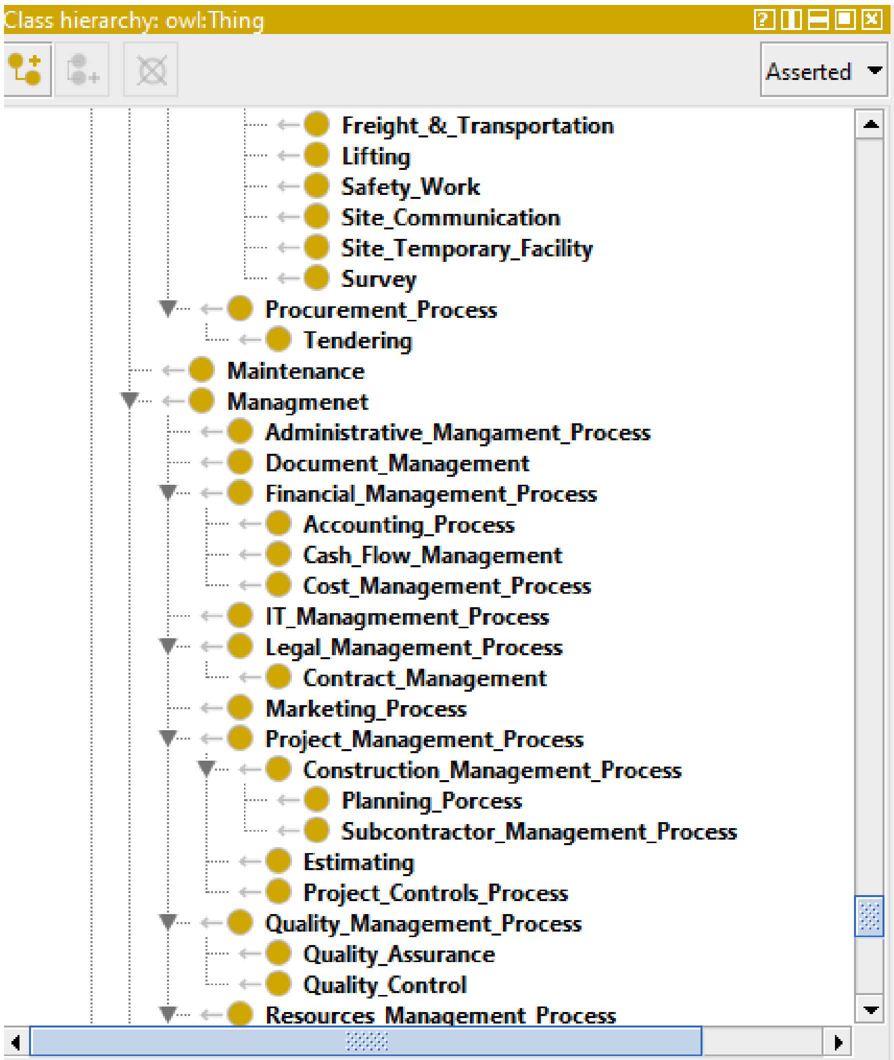
Appendix C- Figure 18: Construction Ontology Concepts (protégé) (16 of 21)



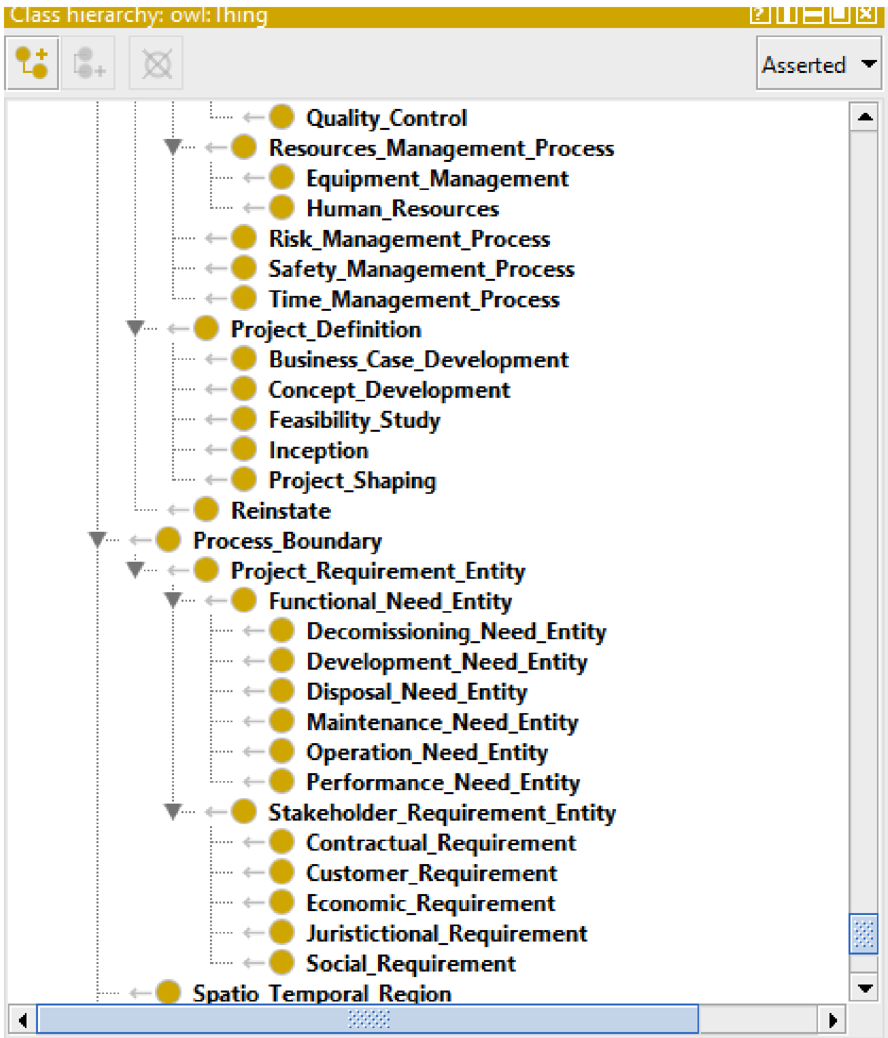
Appendix C- Figure 19: Construction Ontology Concepts (protégé) (17 of 21)



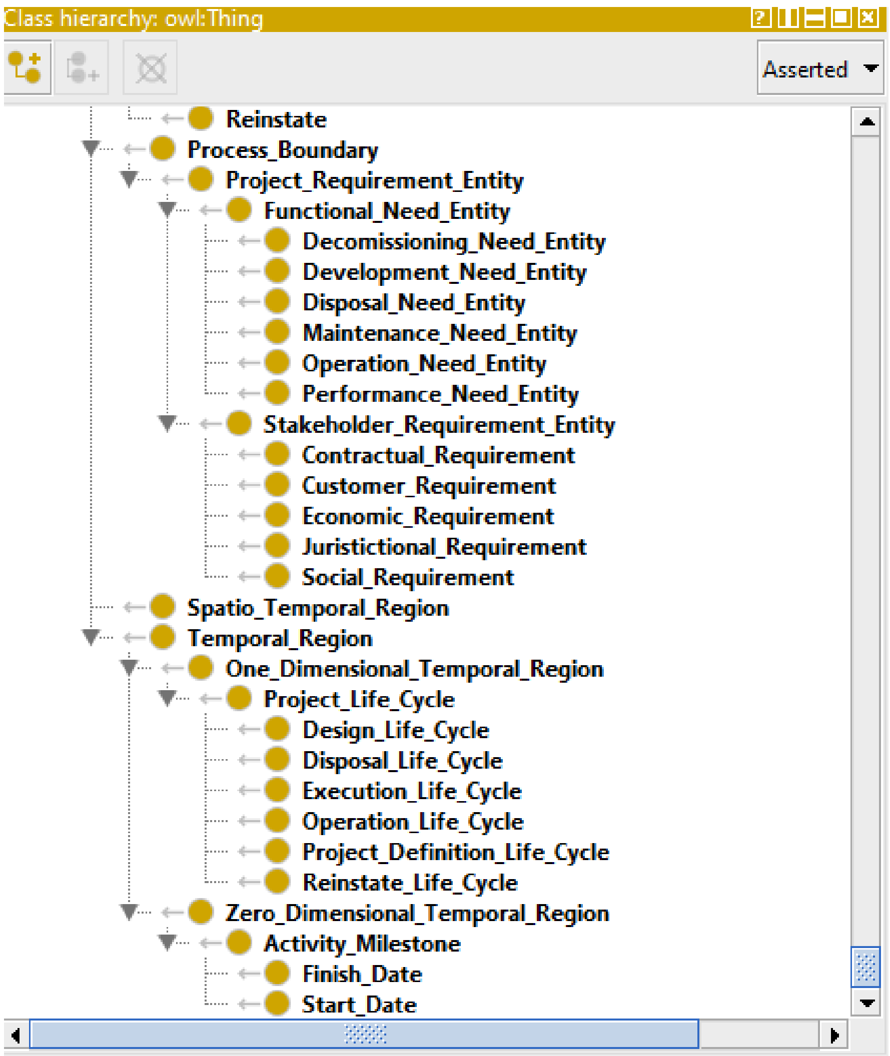
Appendix C- Figure 20: Construction Ontology Concepts (protégé) (18 of 21)



Appendix C- Figure 21: Construction Ontology Concepts (protégé) (19 of 21)

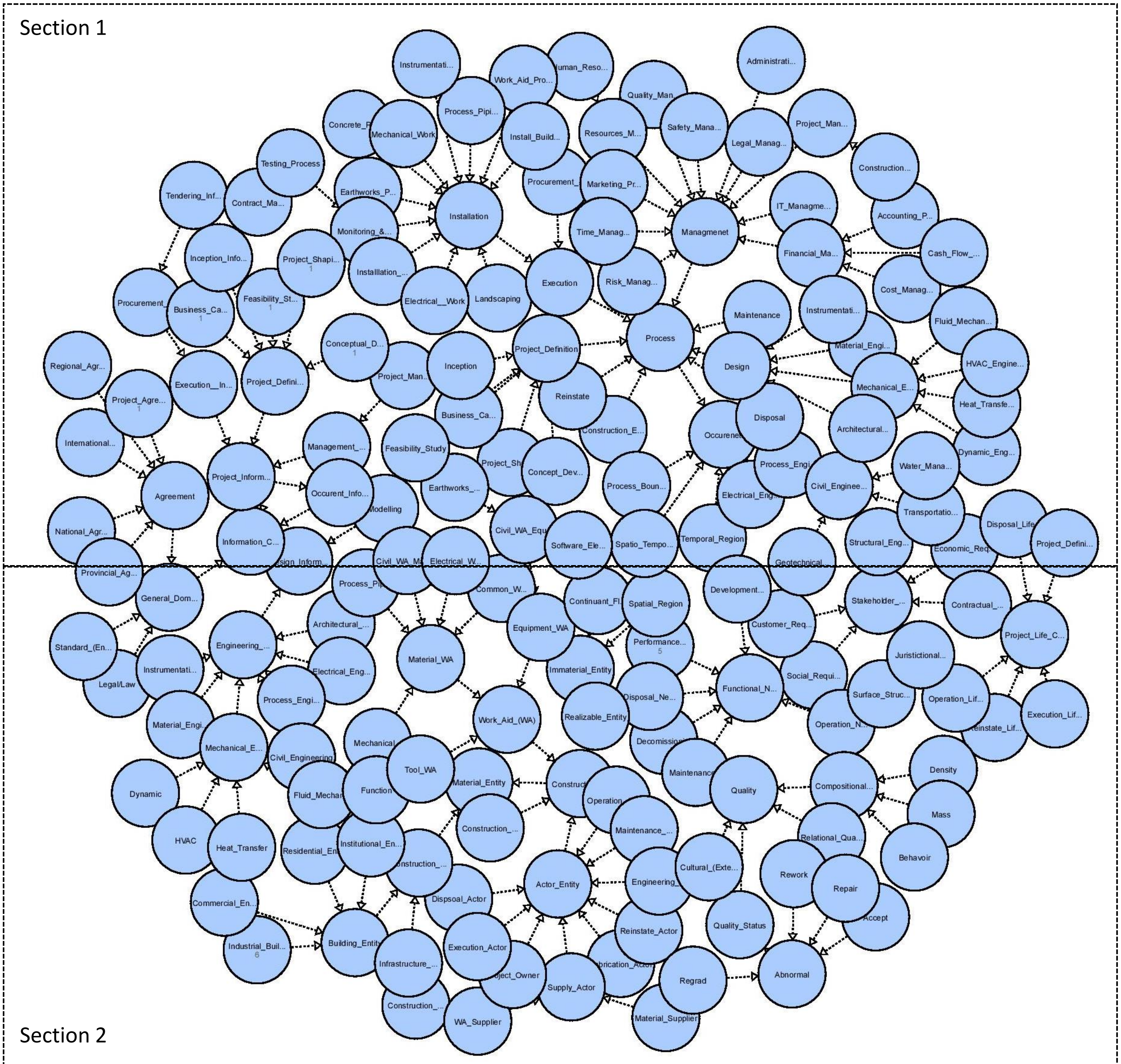


Appendix C- Figure 22: Construction Ontology Concepts (protégé) (20 of 21)

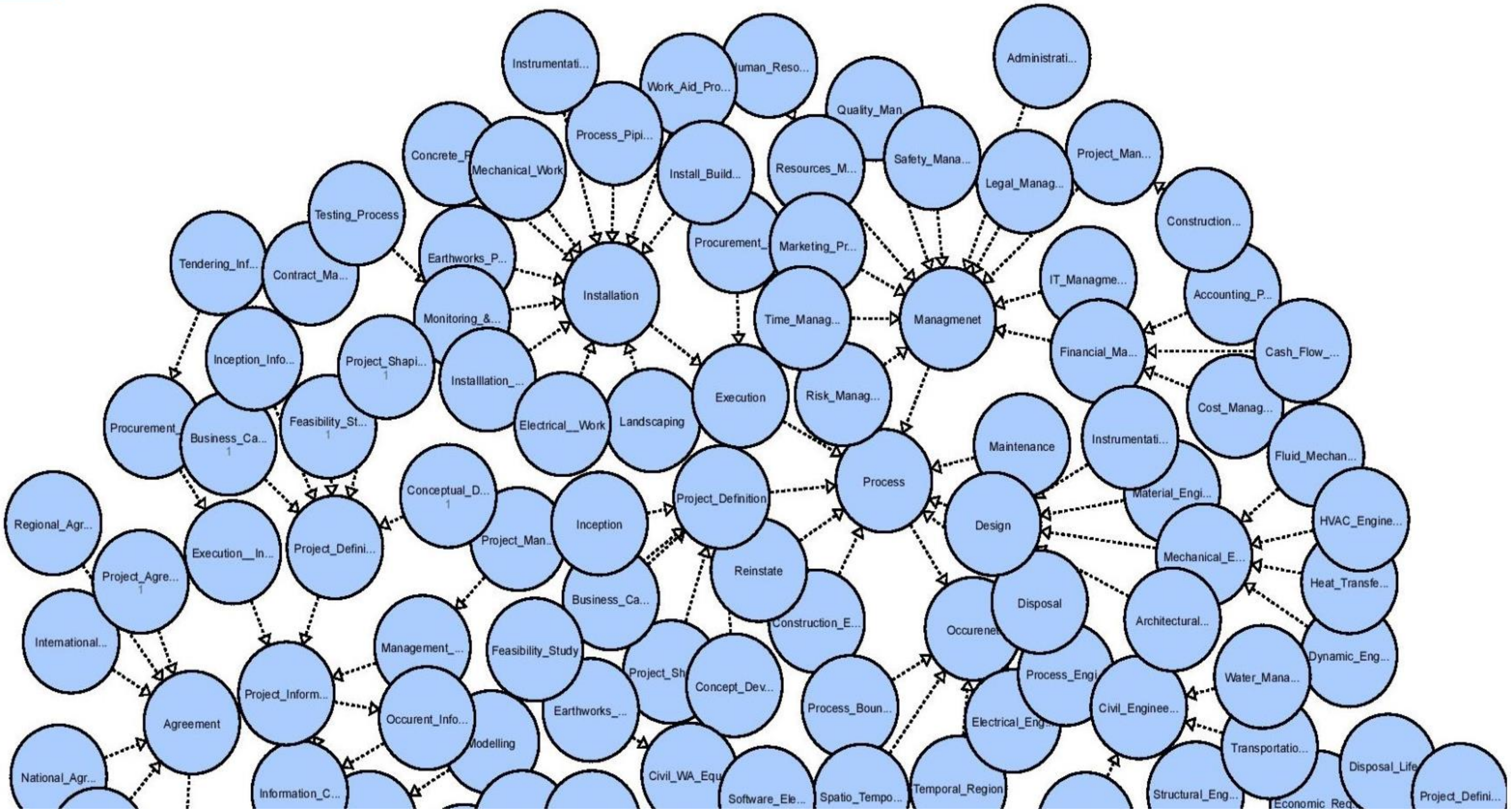


Appendix C- Figure 23: Construction Ontology Concepts (protégé) (21 of 21)

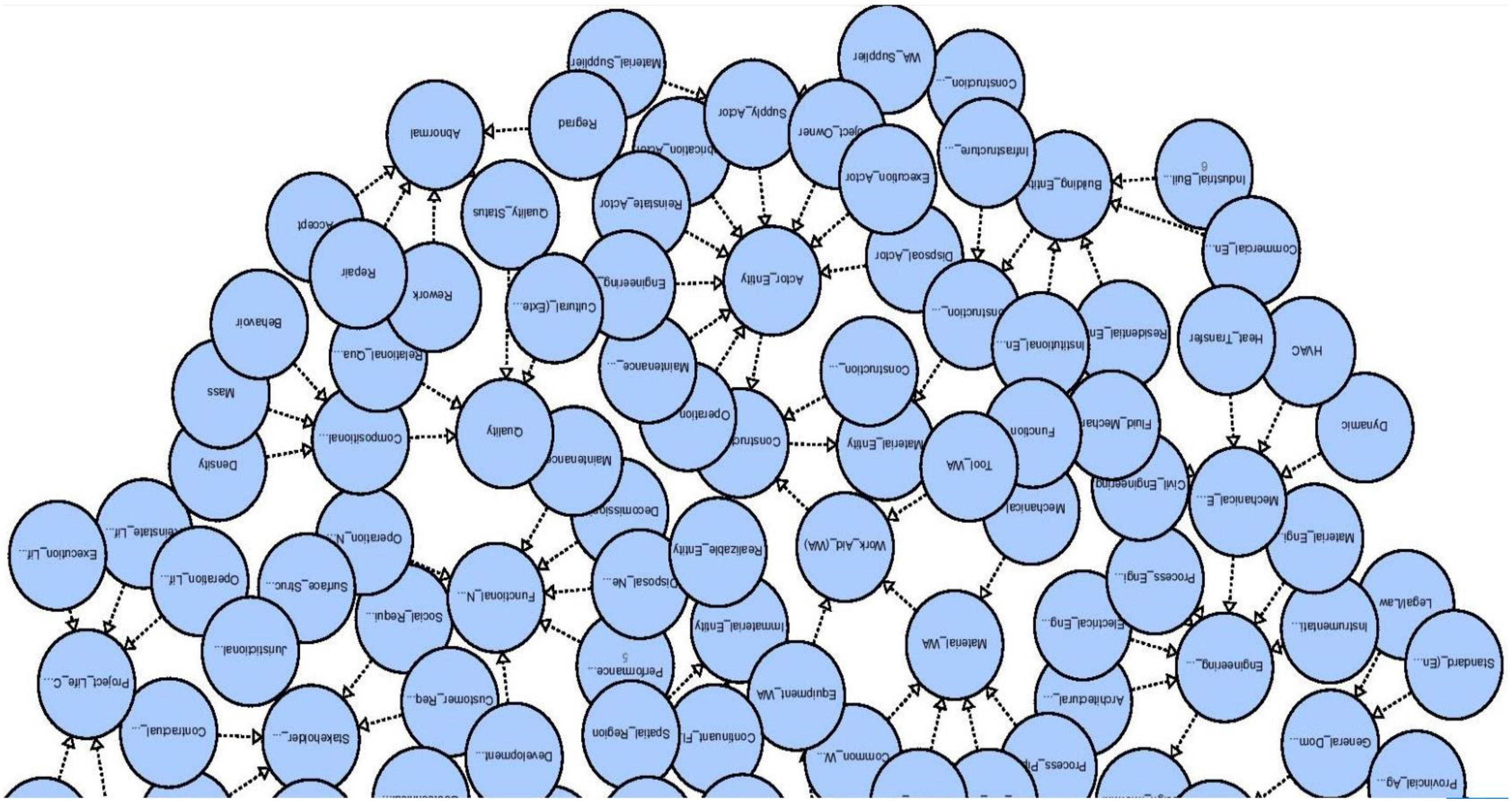
The ontology classes and subclasses are represented using WebVOWLas shown in Figures Appendix C- Figure 24. Figures Appendix C- 25, and 26 are section views of Figure Appendix C- Figure 24. The WebVOWL is a graphical representation of the developed ontology. It shows the classes and their subclasses, which facilitates the understanding of the ontology, [191]. This visual representation can be very useful for users who are less familiar with ontologies as they can follow the structure of the, its concept and their relationships through an interactive tool, [194]



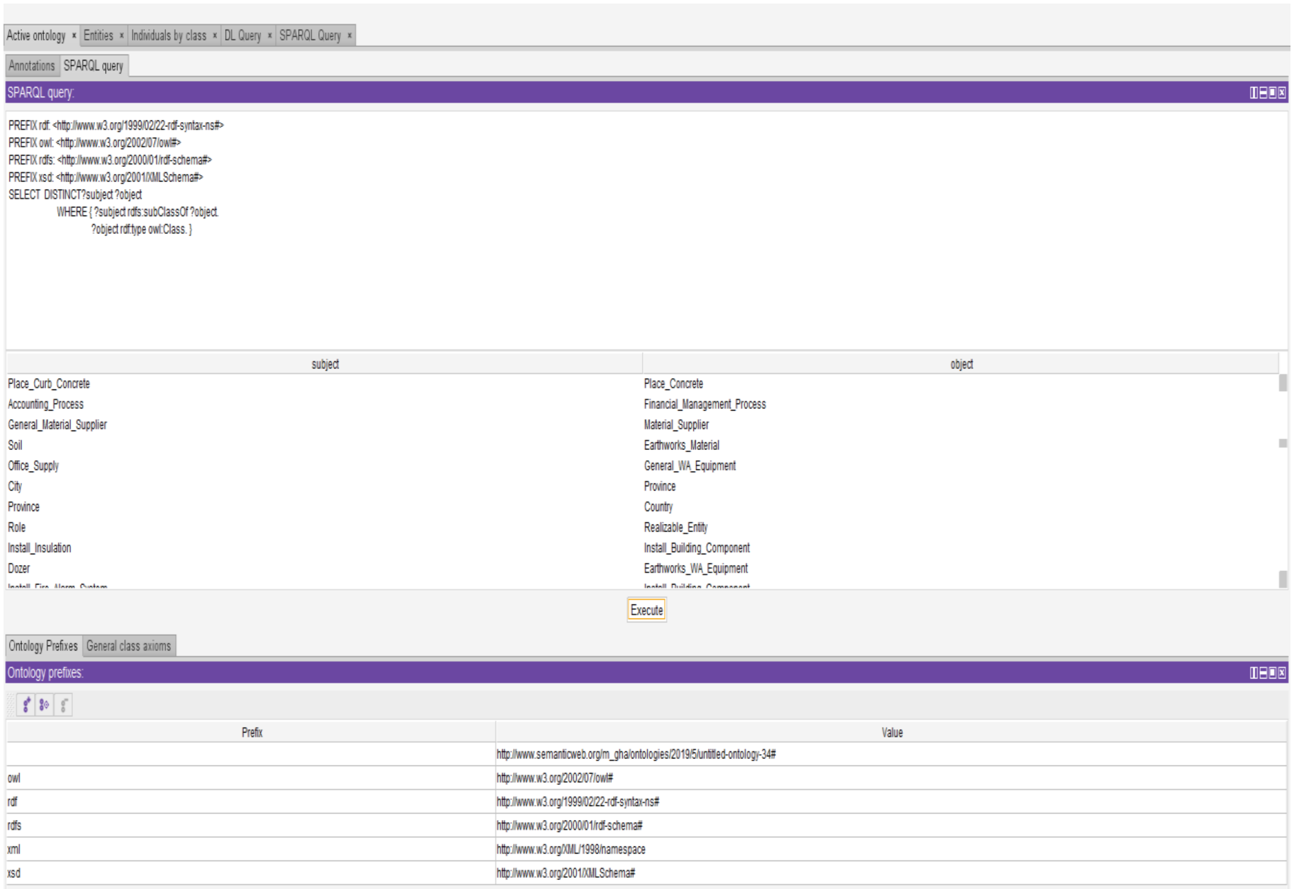
Appendix C- Figure 24: *WebVOWL representation for Ontology Classes*



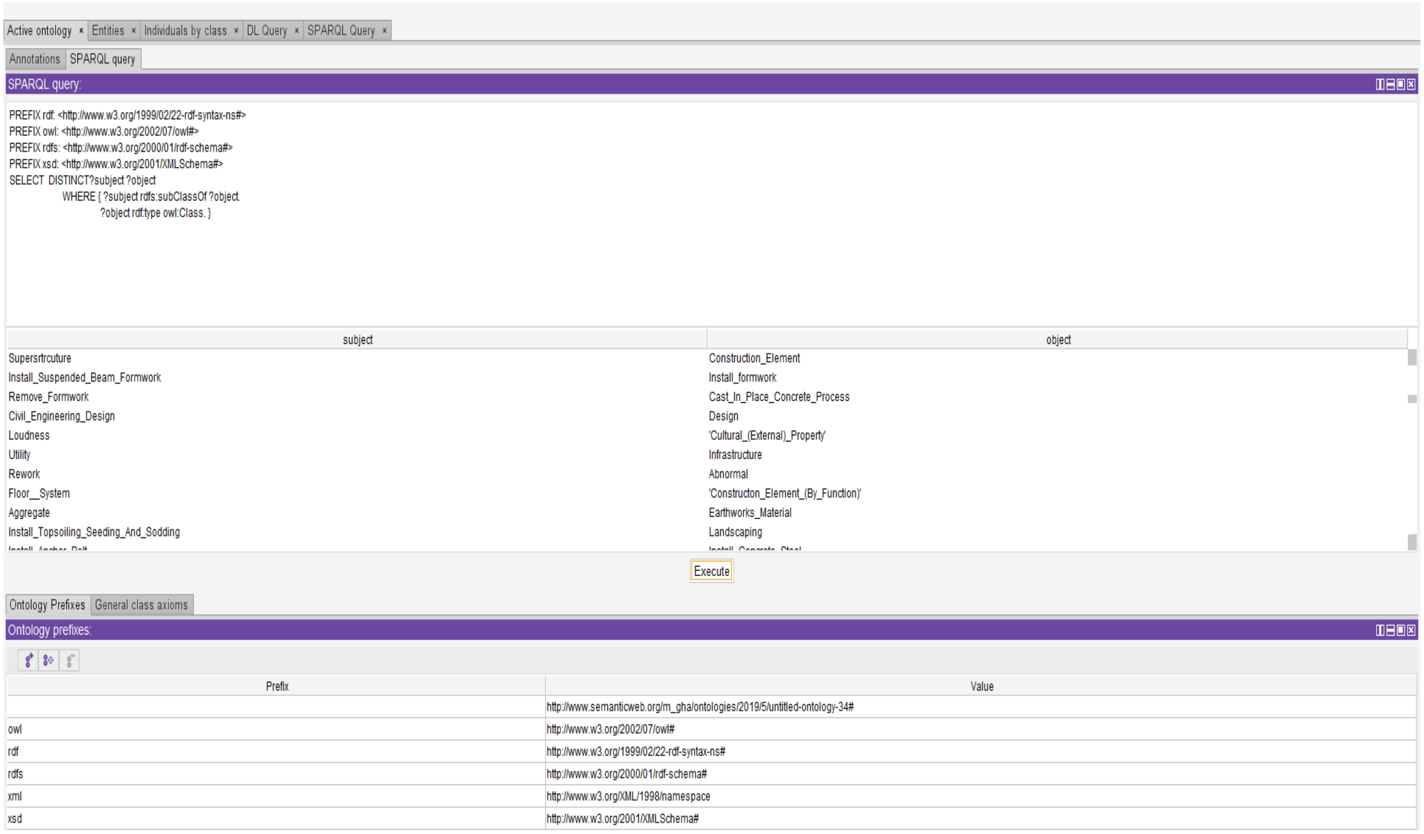
Appendix C- Figure 25: *WebVOWL representation for Ontology Classes- Section 1*



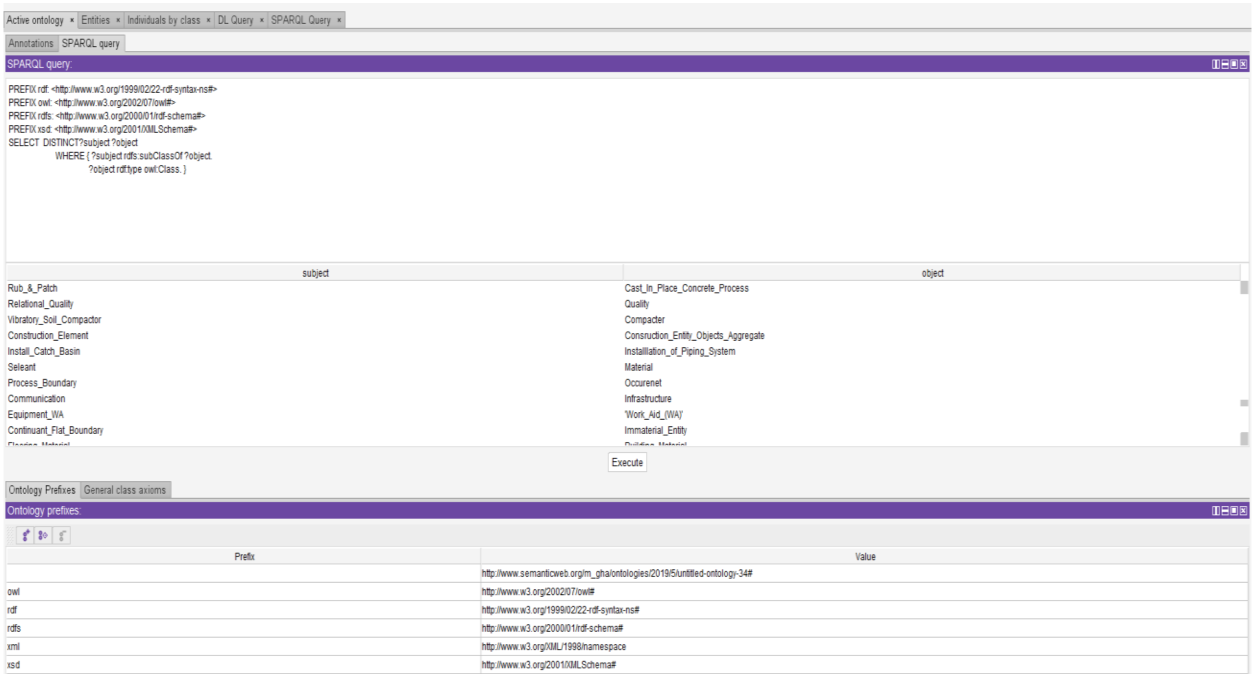
Appendix C- Figure 26: *WebVOWL representation for Ontology Classes-Section 2*



Appendix C- Figure 27: *SPARQL protégé*



Appendix C- Figure 28: *SPARQL protégé*



Appendix C- Figure 29: *SPARQL protégé*

Appendix D: Survey Questions

The survey questions are sent to all workers in the construction industry to have the largest possible participation. The questions are designed to be simple and multiple-choice answers to make it easier for participants to answer the questions.

	Question
0A	**How long have you been working or worked in the construction industry?** 0-5 years 5-10 years More than 10 years
0B	**How would you classify the company you work for?** Owner, General contractor, supplier, subcontractor, engineering, consultant
OC	**Which construction sector you are working or worked in?** Industrial, Commercial/Institutional, Residential, Infrastructure, Multiple sectors
1.	**How many daily, weekly and/or monthly meetings do you attend?** Answer: 0, 1, 2, 3, 4 or more
2.	**In the meetings you usually attend or attended, how often meetings minutes are taken/recorded?** Answer: Always – Often – Sometimes – Seldom – Never
3.	**Do Meeting Minutes capture all information shared in these meeting?** Answer: Strongly Agree, Agree, Disagree, strongly disagree
4.	**If meeting minutes are captured, Do they get distributed to the attendees?** Answer: Always – Often – Sometimes – Seldom – Never
5.	**Do meeting minutes get filed in a system and become available and accessible to all stakeholders i.e. others who needs the information but didn't attend the meeting?** Answer: Always – Often – Sometimes – Seldom – Never
6.	**How often do you refer to meeting minutes to make decisions?** Answer: Always – Often – Sometimes – Seldom – Never
7.	**How often do you use phone calls and face to face discussions to share project related information?** Always – Often – Sometimes – Seldom – Never
8.	**Do you document phone calls and face to face discussions?** Always – Often – Sometimes – Seldom – Never

9.	**Do you file your phone calls and face to face discussion notes, so project team and other stakeholders have access to them?** Always – Often – Sometimes – Seldom – Never
10.	**How often do you use your email to exchange information?** Always – Often – Sometimes – Seldom – Never
11.	**Do you file and share information you received or sent by email with the project team?** Answer: Always – Often – Sometimes – Seldom – Never
12.	**Are you satisfied with email response time? i.e. how often do you receive the information you need in timely fashion to make decision?** - Fast response and no delays on decision making - Sometimes people response late which impacts and may delay my decisions - People always late and have significant impacts on my decisions
13.	**Do you use an information management system to exchange information with interior or exterior stakeholders?** Yes, no If yes, please list________________
14.	**Do you use hard copies such as printed reports, mail, etc to exchange information?** Yes, no
	If yes, do you receive the information in timely manner? i.e. are you satisfied with hard copy as an effective tool to exchange information? Yes, no
15.	**In material purchasing process, does your company use hard copy purchase orders?** Answer: Yes, no if no what kind of system do you use?
16.	**During tender phase, how do you receive the tender package?** Answer: hard copy, email, through information management system, all of the above, others
17.	**How do you communicate with owners, subcontractor/suppliers during tender stage?** Answer: emails, phone calls, hard copies, all of the above, others
18.	**How does your company communicate with suppliers/subcontractors to request quote for material, equipment, etc?** Answer: emails, phone calls, hard copies, all of the above, others
19.	**When do you usually order the materials that you need in your construction project?** Answer: Just in time to be installed, i.e. minimal or no storage time At the start of the project and store it onsite Randomly i.e. no set plan for when the materials should be purchased

Following questions are related to KPIs, to determine what are the most important KPIs in the industry. Questions 19 and 20 to determine if the industry currently implementing these KPIs?

20.	**Select the Key Performance Indicators (Business objectives/goals) important to your organization and rate the importance level?**	*1-Not important*	*2-less important*	*3-important*	*4-Very important*
	Safety Performance	☐	☐	☐	☐
	Information management	☐	☐	☐	☐
	Overall cost reduction	☐	☐	☐	☐
	Performance improvement	☐	☐	☐	☐
	Waste Reduction (Physical and non-value-added activities)	☐	☐	☐	☐
	Quality improvement	☐	☐	☐	☐
	Productivity improvement	☐	☐	☐	☐
	Customer service satisfaction	☐	☐	☐	☐
	Schedule	☐	☐	☐	☐
	*Other*_________________	☐	☐	☐	☐
21.	**Does Your company use quantifiable indicator to measure following Key performance indicators?**	*Yes*	*No*	*KPI example*	
	Safety Performance	☐	☐	such as Rif, TRIF	
	Information management	☐	☐	availability of information	
	Overall cost reduction	☐	☐	labor cost, material and equipment	
	Performance improvement	☐	☐		
	Waste Reduction (Physical and non-value added activities)	☐	☐	Lead time, process time	
	Quality improvement	☐	☐	no. of defects per manhour	
	Productivity improvement	☐	☐	productivity rates target	
	Customer service satisfaction	☐	☐	formal customer feedback in regular basis	
	Schedule	☐	☐	rate of completing projects on time	
	*Other*_________________				
	*Other*_________________				
	*Other*_________________				
	*Other*_________________				

22.	**Do you select you contractor/ subcontractor, supplier based on defined criteria or kPIs?** Cost Only Defined Criteria and shared with all stakeholders Defined criteria but not shared with all stakeholders No defined criteria i.e. project based
23.	**Are you familiar with lean management tools? e.g. PDCA, Kanban, Pull System, etc** Yes, no
24.	**Have you ever used any lean management tools/techniques in your job or project?** Yes, no
25.	**If you have used any lean management tool, please name it and name the process or task you used it in:**
26.	**Have you ever used Value Stream Mapping (VSM) to identify waste in any process as part of your job?** Yes, no
27.	**If you have used VSM before, to what kind of process did you map?** Design phase, tendering, execution of site work, procurement, project controls, project Turnover, others
28.	**If you have any experience with VSM as part of your job, please briefly describe your experience (Efficient tool, hard to apply, in suitable for construction, etc)**

Appendix E: Interview Questions

Interview Questions – Lean Management

The interview questions were directed to professionals who have management and leader roles. The objective of the interview is to determine the current tools and techniques the managers use to improve the work processes and efficiencies. The answers are used to determine if the construction industry currently using lean management tools directly or indirectly.

a. Can you please introduce your current position, types of projects you work on, experience and academic background?

b. Are you familiar with lean management tools and techniques? If yes can you, please illustrate how do you use them in your job?

c. Are you familiar with different types of wastes a process can have?

d. Do you use any tools/techniques to measure your process efficiency?

e. How do you usually increase the efficiencies of processes in your company or project?

f. How do you find the root causes of a problem you have in your project or company?

g. how do you measure the "value" of the product or service your company offer to customers?

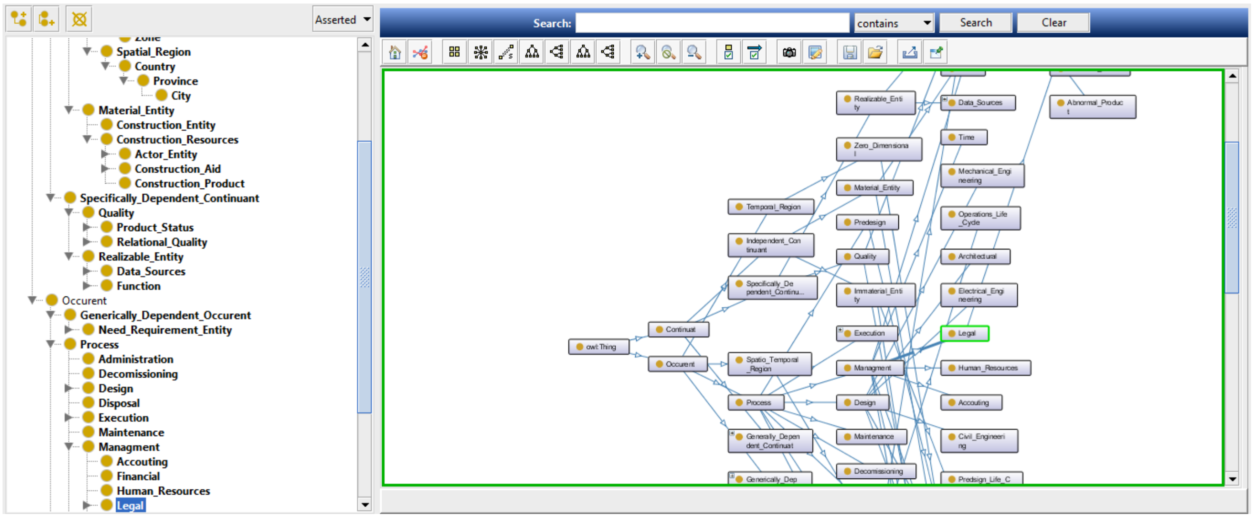
h. Value Stream mapping is a tool used to identify the value-added activities in processes, and also sort out possible non-value-added activities. Have you used value stream map in projects or company before? How do you set the value stream for projects?

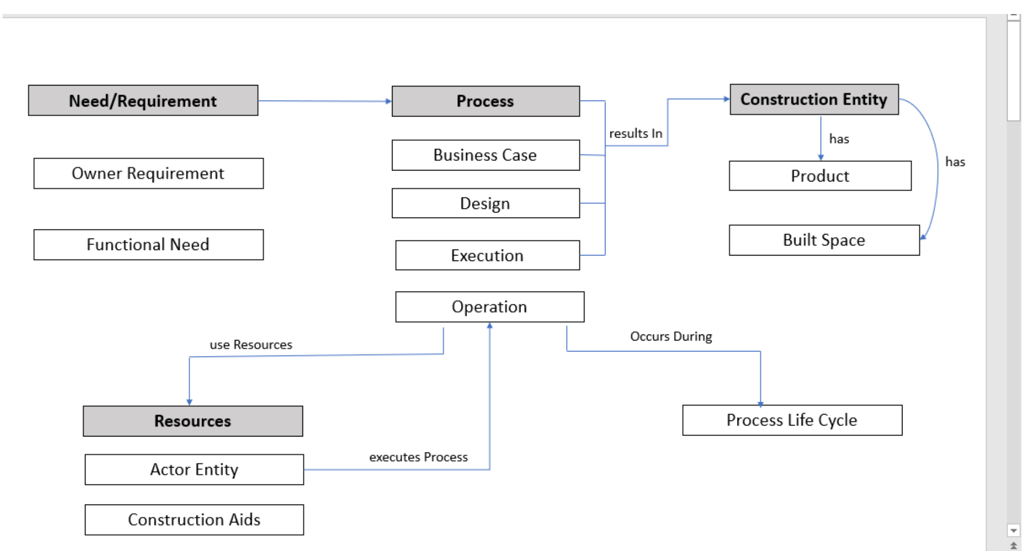
Appendix F: Interview Questions- Ontology Development

The interview questions will be directed to professionals who have management and leader roles within the industry. The objective of the interview will be to have an expert opinion and share their experiences in the industry to develop an information flow system. The answers will also be used to develop the framework as well as the concepts and relations for an Ontology.

a. Can you please introduce your current position, types of projects you work on, experience and academic background?
b. The experts will be asked to review the developed ontology and comment on the concepts, attributes and the relation between these concepts to ensure current industry practices are implemented in the ontology and the framework.

Following is the Ontology that the participants will be asked to review:





Appendix G: Interview Questions- Ontology Evaluation

The construction ontology was evaluated through a competency questions asked for experts. Following are the questions:

I- Does the Ontology represent the Architectural, Engineering and Construction Concepts?

1. Strongly Disagree 2- Disagree 3- Neutral 4- Agree 5- Strongly Agree

II- Is it easy to understand and follow the ontology?

1. Strongly Disagree 2- Disagree 3- Neutral 4- Agree 5- Strongly Agree

III-Is it easy to use and apply at your work?

1.Strongly Disagree 2- Disagree 3- Neutral 4- Agree 5- Strongly Agree

IV- Can you use it as framework to structure the data at your organization?

1.Strongly Disagree 2- Disagree 3- Neutral 4- Agree 5- Strongly Agree

V- Do you think the Construction industry may adapt the framework or concept?

1.Strongly Disagree 2- Disagree 3- Neutral 4- Agree 5- Strongly Agree