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Towards an advanced work packaging simulation-based approach for industrial construction projects

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Abstract
Planning and scheduling construction industrial projects is considered one of the most challenging tasks due to the nature of these projects. Often, the project delivery method of these projects follows the fast-track approach, where there is a lack of detailed engineering information in the early stage, and the construction overlaps the design phase. As such, advanced work packaging (AWP) and planning of the projects at this early stage remains an issue that faces the construction professionals. This research focuses on developing a simulation-based approach for advanced work packaging, planning and scheduling of industrial projects in the early stages. The approach deploys simulation techniques, that utilize historical data, to divide the project into several construction work areas (CWA), to identify various construction work packages (CWP), and finally to specify a defined set of activities or Installation work packages (IWP), resulting in a schedule that can be of aid to the project stakeholders during the early project stage. To verify the proposed concepts, a case study of an industrial project located in Canada, is presented and the output of the simulation model is discussed. The results were validated by experts in the field, and they highlighted that there is a great potential for the simulation-based scheduling approach especially that the model allows for updates, by feeding real-time as-built data once the project commences and this data become available.

Keywords: Advanced work packaging (AWP); industrial projects; simulation; planning; scheduling

1. Introduction

Advanced work packaging (AWP), developed by a joint venture between the Construction Industry Institute (CII) and Construction Owner Association of Alberta (COAA), is a planning and execution approach that focuses mainly on capital and industrial projects, it differs from the conventional methods, that often divides the projects into smaller manageable packages according to the Project Management Institute (Project Management Institute, 2017). The main difference lies in the concept of being construction driven; AWP aims to create a workflow that is free from constraints so that the execution of the works can take place without any delays or disruptions (AWPOKB Advanced Work Packaging Open Knowledge Base, 2018). A research team formed by the CII (Construction Industry Institute, 2011), in their report, RT-272-1, highlighted that the AWP concepts target a main objective which is the alignment of engineering, procurement and construction via the development of work packages, and this paves the way for an improved planning approach throughout the project. Nevertheless, projects still suffer from delays and cost overruns, resulting in probable disputes during project execution.

It was reported by McKinsey & Company (2016) that capital projects often exceed their budgets by a tremendous percentage, that can reach as high 80%, and face delays as well. These delays exceed the project baseline by 20%. In addition, it was reported that oil and gas projects suffer from huge delays and that barely 19% of these projects are completed within the estimated time for completion. Similarly, power generation projects face great challenges as well and delays that hinder the projects' completion in a timely fashion, resulting in only approximately 34% of these projects to be completed on time (CIOB , 2008).

For decades, construction simulation has been used to mimic construction operations in an attempt to produce an enhanced construction management environment that leads to successful project delivery (Halpin, 1973). However, as mentioned previously, construction projects, specifically industrial ones, still suffer from delays and cost overruns. AWP has the potential to standardize the workflow and align the engineering, procurement and construction of projects so that better performance can be achieved. However, simulation models that are built based on the concepts of AWP remain relatively unexplored. This paper aims to provide steps towards the development of simulation models that take into consideration AWP concepts, rely on the requirements of AWP, and lay the grounds for further developments in the future.

2. State of the art

Advanced work packaging is related to the main concept of dividing the work into small and manageable parts that can be monitored and tracked throughout the project life cycle. The breakdown of the project into smaller parts has led to improvements in several areas, such as: productivity, cost and time. However, it is worth mentioning that the work packaging may differ from one project to another or from a company applying these concepts to another. As such, COAA and CII acknowledged work packaging as a best practice and pushed toward the development of the AWP framework (Raz & Globerson, 1998) .

Ponticelli & O'brien (2015) highlighted that regardless the advancements that took place over the decades in the domain of planning and scheduling techniques, still projects lack a formal and standardized approach, especially in early planning phases. As such they decided to apply the concepts of AWP and test it by comparing 2 cases studies, one that follows conventional methods of work packaging, and the other one follows the procedures and guidelines of AWP. Both projects were industrial ones, which is the focus of AWP, and had similar scopes of work as well to make sure that the comparison was valid. They stressed that the application of AWP resulted in better performance pertaining to 4 areas that are the essence of construction projects, namely: cost, time, safety and quality.

Ribeiro (2020) defined AWP as a work packaging concept, that is construction driven, and this is what differentiates it from the traditional work packaging approach. They claimed that even though AWP has been reported to improve the delivery of construction projects, its application remains minimal within construction companies. Accordingly, their research focused on offering solutions to overcome barriers hindering AWP's spread and implementation in various companies. Ribeiro (2020) conducted interviews with 16 experts in the field to gain insights on why AWP is still not a common practice in the industry and how to overcome these issues.

O'Connor et al. (2022) studied the previous research on AWP and how this research could be advanced to cater for commissioning and startup (CSU) for industrial projects. They claimed that most of the research that focused on AWP was related to the execution phase and the CSU was overlooked. As such, in their study, they reached out to industry experts and investigated the current body of knowledge to find grounds that substantiated their idea of incorporating CSU in AWP. Their research resulted in the development of a new concept, called systems work package (SWP). They highlighted that this new concept leads to cost savings and more importantly enhances collaboration between the different parties.

Guerra et al. (2020) stressed that project failures together with disputes is highly probable in the industry, so AWP might be a potential to minimize those Issues throughout the project and results in a higher probability for successful project delivery. However, they highlighted that the integration between the engineering and construction deliverables are not properly aligned, specifically, the 3D models. As such, in their research they conducted interviews with construction professionals to identify the obstacles facing this Integration between 3D models and construction during the execution of the works.

Taghaddos et al. (2021) introduced a framework that focuses mainly on resource optimization and congestion problems that occur during the execution of the works in industrial projects, they highlighted that their framework benefits the concepts of workface planning (WFP) and discussed its application on multi-mode activities' networks.

As mentioned, in the introduction section, a major goal for AWP to achieve, is providing an environment that is free from constraints so that the execution of the works can take place smoothly without interruption of crews being idle. Wu et al. (2021) introduced in their research a hybrid deep learning model that automates constraints extraction, which is a cornerstone in the advanced work packaging approach. A bidirectional long short-term memory and conditional random field model were developed. These models were utilized in extracting entities and relations, and can scan through text documents to define constraints. They concluded that the model has a high accuracy in specifying the constraints, and they mentioned that the framework can be applied on the ongoing projects resulting in time saving and rework minimization as well.

The previously discussed literature review presented the efforts directed towards AWP and how this approach is considered as an improvement to the planning and scheduling of industrial construction projects. However, these approaches mainly focus on the theoretical background of AWP and its implementation in the industry. However, to the authors' knowledge, none of these research studies discussed the application of construction simulation approaches in AWP, and this area remains relatively unexplored. As such, this paper aims to develop a simulation model that takes into consideration the core concepts of AWP, and discusses the breakdown of the project into construction work areas (CWA), construction work packages (CWP) and installation work packages (IWP). This is expected to provide a standardized approach for the planning of industrial projects, especially in the early stages, and pave the way for additional developments in this area.

3. Methodology

3.1. Advanced work packaging

This research aims to provide simulation models that incorporate the core concepts of AWP. These concepts target the standardization and organization of information throughout the project and the alignment of engineering, procurement and construction. Prior to developing the simulation model, the main concepts of AWP are defined to provide the reader with a better understanding of the breakdown of the project and how this translates to the simulation model. The first step is the breakdown of the project into CWA. Once CWAs are defined properly, another level of breakdown takes place, which is referred to as a CWP. CWP is another breakdown of the CWA, that is related to a specific discipline within each specific CWA. Another important term that is essential for AWP is the engineering work package (EWP). EWP is an engineering deliverable that is aligned with the construction sequence, or often called, the path of construction. As such, EWP must be aligned with the CWA and CWP as well. The last term that is essential in the domain of AWP is called IWP, which are considered a breakdown of the CWP, and also relate to the works of specific discipline. An IWP is limited to a small, manageable scope, that can be executed and monitored by a crew within a relatively short period of time that ranges from 1 to 2 weeks.

This research aims to provide a simulation environment that takes into consideration the concepts of advanced work packaging. The proposed model allows for various functionalities that lay the foundations for advanced work packaging simulation-based approaches. These functionalities include: (1) building a simulation model from the database, (2) running the model, and the generating results, (3) inserting actual or as-built data once the project commences, (4) updating the various parameters in the model once a change occurs. Figure 1 shows the methodology followed throughout the study.

3.2. Data structure

Data adaptors are used to retrieve the data, which are then read by the model generator. The function of the model generator is building the model. Next, the model is then run and the simulated scenario together with the statistics related to queue, utilization and the resource profiles are generated. Finally, the output data are written to the database. The database can then be updated with actual or as-built data once a project starts. Also, changes in resource availability, either quantity or changes in their availability throughout the project, can be incorporated into the database. The model is then run again to generate a scenario that reflects the status after the changes.

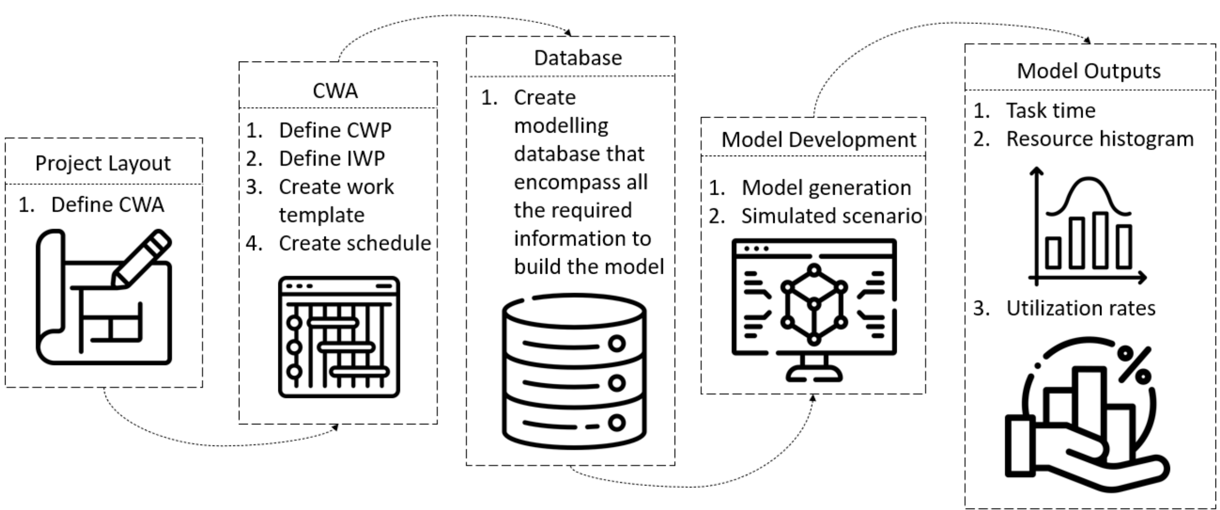

Figure 1 Proposed methodology

Data structures define the different model inputs in the proposed environment or simulation model. These data structures define the different components of the model, represented in tables, that need to be developed in order to cater for the project components.

Data structures were specifically designed to align with the concepts of Advanced Work Packaging (AWP). The fundamental element of the model input is called a "product," which corresponds to a CWP in AWP terminology. The authors followed the recommended approach outlined by the Construction Industry Institute (CII) and Construction Owners Association of Alberta (COAA. In this approach, a CWP can be based on a module or equipment associated with a specific area known as a CWA. Consequently, CWPs represent significant components of the projects and are situated within a particular CWA. Each CWP consists of a set of specific tasks that must be carried out, known as an Installation Work Package (IWP).

For a product to be developed, IWPs need to be identified and logic or dependencies should be followed for a successful delivery of the product. The logic/dependencies between the IWPs are taken into consideration within the template. Each product has a specific template that has been developed to capture the work executed to build this product, the template holds all the logical information.

Once a template is developed showing the various IWPs within a product, the next step is resource loading in order to estimate the manpower required for each IWP. As such, resources are added to the model, showing the number of available laborers throughout the different durations within the project. Following the insertion of resources in the model, crew composition takes place next in the model development process. Simply, the crew composition includes the specific number of laborers that form a crew. More details regarding the data structures and the different tables will be discussed in the next sections.

The first table, product table (Table 1), deals with the element or component to be built, for example, boiler, in the project.

Table 1. Product input fields.

Field	Description
ID	Unique identifier
Product	Descriptive identifier for the product
Qty	Quantity to be built
Template	Descriptive name for the template
Parent	Name of the parent product for a child product

The second data table (Table 2) is called the template table, this table deals with parameters/fields that include, lag, resources required to perform the activity, quantities, and productivity. The crew productivity can be added to the model in 2 different ways, the first one is to be included as a constant value or it can be input as a stochastic rate, that can be represented by various equations where their parameters can be defined, then the rate can be sampled from that equation. Another subset of the table represents the various activities that take place together with their sequence, and by sequence, it means the different relationships that can exist between the activities, such as: first to start, start to start, finish to finish, and start to finish.

Table 2. Template input fields.

Field	Description
ID	Unique identifier
Template	Descriptive name for the template
Task	Descriptive name for the template
Qty_M	Multiplier to calculate task quantity
Qty_K	Constant value added to task quantity
Resource type	Name of crew
Productivity	Productivity rate (constant or stochastic)
Level	Product hierarchy level
Persist	Indication for the continuation of the resources from the first task to the final task
Cumulative	Indication for the cumulative value of a task
Version	Date stamp of record
Sequence fields	
ID	Unique identifier
Template	Descriptive name for the template
Predecessor	Name of predecessor activity
Successor	Name of successor activity
Version	Date stamp of record

Another table (Table 3) deals with the crew composition, which defines the different composition of the crews, and what type of labor or equipment they include. Also, it includes fields related to the availability of the crews within a period of time; accordingly, it allows for the variability in resource availability within a project, that reflects a more realistic view to the real-life situation throughout the project. The quantity of resources in this table differs from the one in Table 5 as this one here relates to the available quantity throughout the project; while the one in Table 5 shows the profile or utilization throughout the project.

Table 3. Crew and resource input fields.

Field	Description
ID	Unique identifier
Resource type	Descriptive name for the required crew
Resource	Descriptive name for the resource
Number	Quantity of resource required in a crew
Version	Date stamp of record
Resource availability fields	
ID	Unique identifier
Resource	Descriptive name for the resource
From	Start date for the resource availability
To	Finish date for the resource availability
Quantity	Quantity of resource available in the specified period
Version	Date stamp of record

The last table, the environment data table (Table 4), focuses on the general project information and it is comprised of 2 sections. The first section pertains to the project calendar, resource calendar, that defines the working hours and shift information. The second part is called the setup table and it focuses on the modeling parameters, such as: the random seed, start date of the project and the number of runs required by the user.

Table 4. Crew and resource input fields.

Field	Description
ID	Unique identifier
Calendar	Descriptive name for the calendar
Resource	Descriptive name for the resource
From	Start date of the specified period for record
To	End date of the specified period for record
Shift From	Start time of shift
Shift To	End time of shift
Version	Data stamp of record
Calendar Setup Fields	
ID	Unique identifier
Parameter	Descriptive name of the parameter
Parameter Value	Value of the parameter

3.3. Model development

The model generator works using a custom-made, internally developed software program, Simphony Dynamic, that accesses the data from the input tables in the database and creates a corresponding Simphony Dynamic model. The Simphony Dynamic model includes a hierarchical structure and integrates components or different tables specified in the database, such as crew availability and templates. The model connects to the modeling database, enabling product data to be accessed during the simulation process and simulation outcomes to be saved back to the database.

The simulation model can be built using 2 approaches. The first approach is importing the model into Simphony Dynamic and once uploaded, the model can be viewed, changed, and run. The second approach is using the user interface to build all the templates, dependencies, resources and any other components of the model. In this research, the second approach is used where the whole modelling process is performed using the user interface. In either case, the simulation process unfolds as follows: initially, a connection to the database is made, and the Product input table is accessed, that reflects the various components of the project that need to be built, and each product is allocated a to a template. Subsequently, the discrete-event simulation occurs, with entities representing products moving through their corresponding sub-models. While running the simulation model, statistics are generated and saved in a continuous manner. Once all the products/project components are run, and the simulation models come to a halt, a connection is reestablished with the database, and the output results are written to output tables.

3.4. Model outputs and updates

Once the simulation model is run, statistics are saved in the output tables (Table 5) and are used to aid the construction professionals in the decision-making process. The professionals can use these outputs to understand how operations will proceed throughout the project, queuing information and resource utilization. The simulation model provides a valuable tool, especially in the early stages where detailed engineering data is not yet available.

Additionally, professionals can make use of the work templates included in the model. The templates can be reused when developing a model for a similar project, and slightly modified for the requirements of that project. By reducing the time and effort required to develop future simulation models, the adoption and implementation of these models can be accelerated.

Table 5. Output fields.

Field	Description
Activity time	Start and finish date and time
Resource usage	Utilization level throughout the project
Queuing	Queue information related to products for different crews
Statistics	General statistics generated when the simulation is runf

The output data or statistics are written to the database to be studied by the construction professionals. Once the project commences, and actual data becomes available, the model can be updated using the actual or as-built data. The model also offers flexibility for the modification of various parameters, including resource availability, which is highly probable to change at the start of the project. Additionally, crew composition may vary from one product to another throughout the execution of the works. Other parameters that can change during the execution phase are the activities and the sequence too. Activities may vary from the work template that is used to run the model in the early stages. The model allows the users to change the activities in the template and change the relationships as well. Finally, the general project information can be changed as well depending on the circumstances and status on-site. As such, the user can modify the parameters, deemed necessary, and include the actual data, then the link between the database and the simulation engine is reestablished and the model is run using the as-built data.

4. Illustrative example

To verify the applicability and functionality of the developed model, it was tested on case study of an oil sand project, an industrial project located in Canada. The project is divided into several CWAs, as shown In Figure 3, and each area contains various products or modules that often involve cranes for lifting and installation of these modules. For the purpose of this research, only six products were selected from the project. Historical data were analyzed, and several sessions took place with subject matter experts to identify a set of predefined tasks, referred to as a template. This set of tasks are the ones that are commonly executed for the completion of each specific product. Afterwards, the dependencies between the different tasks were added coupled with the appropriate lag.

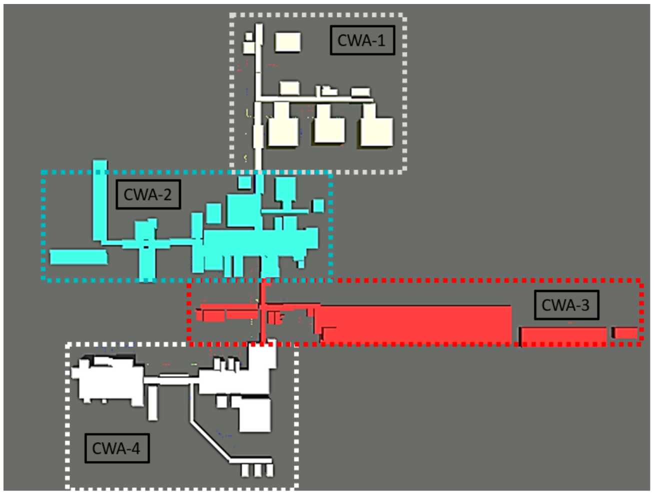

Figure 2 Project layout.

4.1. Simulation model

The six products belong to the same CWA, and they vary from piperack, pipe stick built, and tanks. A predefined sets of tasks or IWPs has been developed and the one for the piperack is shown in Table 6.

Table 6. Piperack Tasks.

Name	Duration (days)	Productivity (units per day)
Modules Set	2	0.5
Modules Finish	14	0.07
Piping Hydrotest	7	0.14
Piping Install	14	0.07
Piping Rig	7	0.14
Piping Support	7	0.14
Structural Steel Install	21	0.04
Structural Steel Complete	7	0.14

The duration from historical data was translated into productivity since the software was developed to cater for productivity and quantity rather than duration. Furthermore, productivity is most commonly used in the estimation or early planning phases in order to derive durations so that a preliminary schedule can be developed.

After defining the set of tasks or IWPs and inputting the productivity of the tasks, a resource dictionary is created to add the available resources to the model. The model allows the variability of resources throughout the project, so the construction professional can add different resource quantities throughout a period of time. This allows for mimicking the resource availability through the project lifecycle. Furthermore, it is possible to allocate the same crews to multiple products within the simulation, enhancing its authenticity by mirroring the scenario in real construction sites where a single crew can be responsible for several products. Once the resources are defined, the next step is the definition of crews and their composition, for example, an electrical crew is comprised of 2 electricians, a pipe fitting crew is comprised of 3 pipefitters, the rest of crews were developed in a similar fashion. Afterwards, each crew was assigned the relevant IWP. Finally, the products (i.e., piperack, tank) were defined and each product was assigned a template, created in the previous steps. A screenshot of the bottom piperack is shown In Figure 2.

4.2. Simulation model outputs

The model outputs are stored in a database in 4 main tables, these tables relate to the six products, 1) crew file length, 2) crew waiting times, 3) resource utilization and 4) simulated timings. Screenshots from the output tables are shown in tables 7, 8, 9 and 10.

Table 7. Crew file length.

Date Time	Crew ID	File Length
2/14/2014 8:00	6	0
2/14/2014 8:00	7	1
2/14/2014 8:00	8	3
2/14/2014 8:00	9	1
2/14/2014 9:09	9	2
2/14/2014 10:19	9	3
2/14/2014 14:41	3	1

Table 8. Crew waiting times.

Crew ID	Product ID	Task ID	Waiting Time
3	2	9	273.24
3	4	9	255.38
3	5	16	104.64
3	5	17	276.07
3	5	18	0
3	5	19	123.56

Table 9. Resource utilization.

DateTime	Resource ID	Total	In use	Available
5/1/2014 11:31	8	25	21	4
5/1/2014 14:56	8	25	18	7
5/7/2014 11:57	8	25	15	10
5/9/2014 10:17	8	25	12	13
5/14/2014 8:35	8	25	9	16
5/18/2014 0:00	3	4	3	1

The crew file length table serves to specify the queue length for a particular resource, with the length of the file indicating the number of entities that are currently

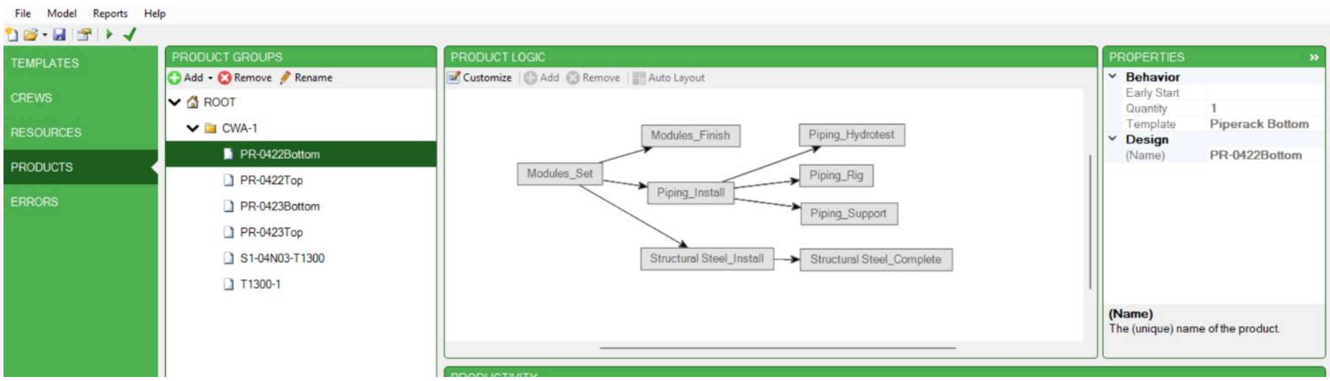

Figure 3 A piperack product

Table 10. Simulated timings.

ProductID	TaskID	StartDate	EndDate
1	1	2/14/2014 8:00	3/21/2014 14:42
1	2	2/14/2014 8:00	3/20/2014 17:00
1	3	4/22/2014 10:23	5/1/2014 11:31
1	4	2/14/2014 8:00	4/28/2014 10:49
1	5	2/14/2014 10:19	2/25/2014 11:27
1	6	3/7/2014 16:22	3/19/2014 8:31
1	7	4/18/2014 8:34	4/29/2014 9:43
1	8	3/21/2014 8:00	4/24/2014 17:00

waiting. The resource utilization table shows the number of resources available within a specific period and the numbers that are in use at the same time. As such the utilization rates can be analyzed and the resources can be reassessed or reevaluated to check the feasible quantities that should be available to execute the works on site. Furthermore, it helps in identifying any shortage in manpower throughout the execution phase. Finally, the simulated timing table shows the start and end date of the activity or IWPs, which provides a sense of direction to the construction professionals regarding the schedule of the project in the early project stages. Once these outputs are analyzed, construction professionals can make informed decisions and adjust their plan according to these outputs and their analysis.

5. Model verification and validation

To ensure the proper functionality of the model, a straightforward case was created for verification purposes. This case included simple dependencies between tasks, with easily identifiable and traceable lags. Additionally, the crews involved in this case were composed of a limited number of resources.

For verification, the same case was solved manually. This manual solution process aimed to confirm that the model successfully executed the necessary functionalities and produced accurate results. Following the verification process, model validation took place by applying face validation, in which an experienced professional with knowledge of the domain of industrial construction projects are asked to assess whether the models appear to be a reasonable representation of the real-world situation it is intended to simulate (Sargent, 2010). The subject matter experts explored the model and validated the various products, activities/IWPs and CWAs. They also assessed the logic with the different lags to ensure that it was valid. They stated that this approach can be extended to include other projects as well. They highlighted that the results showed great potential for the use of the framework in the early planning stages where the available information is not adequate to develop a detailed schedule. As such, this framework aids the construction professionals to develop a simulation-based schedule that applies the concepts of advanced work packaging in the early stages of the project and once as-built data are available, the model can be updated to reflect the actuals and simulate the rest of the project.

6. Conclusions

This research has laid the foundation for developing simulation models that take into consideration the core concepts of advanced work packaging. This includes the breakdown of the project into work CWAs, CWPs, and IWPs. It paves the way for the implementation of advanced work packaging in the early project stages and enables model updates, either in tasks, logic, lag, and actual data once the project commences and as-built data becomes available. Templates for various industrial products or components were developed to cater for the typical activities that often take place while executing this type of work. Next, the logic between the various tasks was added together with resources, crews, and their availability throughout the project. A case study illustrated the functionality of the developed model and its practicality and user friendliness as it requires no prior knowledge in the simulation domain. In addition, it is considered an efficient and time saving tool to build a construction simulation model without the need to go through the erroneous and cumbersome process when using traditional planning and scheduling software. As such, this research adds to the body of knowledge by applying the concepts of AWP in the early stages of the project and it helps construction professionals build simulation models related to these concepts in a more efficient manner.

In addition to its practicality and user-friendliness, the simulation model developed through this research can also be used in a distributed simulation as a federate. This means that the simulation can be integrated with other simulation models to create a comprehensive simulation of a construction project that takes into account various aspects such as schedule, cost, and resource allocation. By using the simulation model as a federate, construction professionals can simulate and evaluate different scenarios to identify potential issues and improve the overall project plan before the actual construction work begins. Overall, this capability of the simulation model further enhances its usefulness in the construction industry.

As highlighted previously, although the model functionality has been demonstrated in a case study, there are still some limitations that are worth exploring. First, data mining techniques and further investigations of the historical data should take place in order to develop templates that accurately reflect the product tasks and the inherent logic. Another feature that the authors would like to investigate is the applicability of adding the start and finish date of the whole project so that the different products and in turn tasks can be completed within the specific duration. In addition, resource levelling techniques to decrease the fluctuation that may arise due to resource allocation and activities' durations can be explored. Despite the value of the developed model and its benefits to the industrial construction projects planning and scheduling, there is still room for model enhancement, by incorporating historical S-curves and resource levelling.

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