IMPROVING CONSTRUCTION ENVIRONMENTAL METRICS THROUGH INTEGRATION OF DISCRETE EVENT SIMULATION AND LIFE CYCLE ANALYSIS

*H. Golzarpoor[1] and V. González[1] and M. Poshdar[1]

[1]The University of Auckland
20 Symonds Street, Auckland 1010, New Zealand
**Corresponding author: hgol431@aucklanduni.ac.nz*

ABSTRACT

Life Cycle Analysis (LCA) is a methodology for evaluating the environmental impacts associated with a product during its life cycle. LCA is identified as the most reliable method for verifying environmental impacts; however, current LCA-based approaches have certain limitations for environmental analysis of construction products. Integration of the LCA methodology with Discrete Event Simulation (DES) provides a sound framework for modeling and analysing the environmental impacts of construction products. LCA and DES is one possible combination for analysing the cause and effect of various scenarios where time, resources, and randomness of input variables affect the outcome and, therefore, has the potential to address the shortcomings of LCA in construction. Recent studies in disciplines other than construction such as manufacturing systems have revealed positive effects on evaluation of environmental metrics while integrating LCA with DES; however, this integration has not yet been applied for environmental analysis of construction products. By implementing LCA data in a DES model, this research proposes an environmental model of earthmoving operations in a case study. Environmental variables are simultaneously assessed with production variables in the same simulation model and the integration of DES and LCA is discussed.

KEYWORDS

Discrete Event Simulation, Life Cycle Analysis, Environmental Analysis, Construction Management

AN INTRODUCTION TO LIFE CYCLE ANALYSIS AND DISCRETE EVENT SIMULATION

The practical implementation of sustainability is a challenge for the construction industry, for which there have been several research efforts to model sustainability (González & Echaveguren, 2012). In this regard, Life Cycle Analysis (LCA) has proven to be a valuable tool to document the environmental considerations that need to be part of decision-making towards sustainability (Jensen et al., 1998; Ness et al., 2007). LCA is a methodology for evaluating the environmental impacts associated with a product during its life cycle. LCA can be accomplished by identifying and quantitatively describing product's requirements for energy and materials, and the emissions and waste released to the environment. A product under study is followed from the initial extraction and processing of raw materials through manufacturing, distribution, and use, to final disposal, including the transport involved, i.e., its entire lifecycle (Johansson et al., 2009). Current LCA-based approaches for environmental analysis in construction sector have three main modeling limitations: (1) LCA lacks a proper quantitative analysis of the uncertain, complex and dynamic nature of production systems. (2) LCA lacks simultaneous assessment of environmental and production variables. (3) The focus of LCA has mainly been on building materials rather than the life cycle of an entire building product. As the traditional LCA has modeling limitations for mapping the environmental loads of an entire construction product including civil and building projects, this research proposes a dynamic modelling framework based on the Discrete Event Simulation (DES) approach to overcome these limitations.

DES models describe systems evolving over time, where state variables change instantaneously at separate points in time (Law, 2007). The main goal of DES is to identify problem areas and quantify or optimize production system performance such as throughput under average and peak loads, utilization of resources, labour and machine, staffing requirements, work shifts, bottlenecks, choke points, queuing at work locations, queuing caused by material handling devices and systems, effectiveness of the scheduling system, routing of material, and finally work in process and storage needs (Lind et al., 2009). DES is able to model and handle complex systems with highly dynamic decision rules and relationships between different entities and resources, and it explicitly includes system uncertainty (Law, 2007). DES has also been recognized as a powerful technique for the quantitative analysis of complex construction operations (Martinez, 2010).

INTEGRATION OF DES AND LCA

Reuter et al. (2004) state that even though the LCA purpose is clear, this is developed under a static approach without involving statistical and/or probabilistic analysis of measures that consider the complex and dynamic nature of production systems. Due to the fact that probability and statistics are core concepts of DES and the capability of DES for quantitative analysis of complex and dynamic production systems, integration of DES and LCA have been proved to be quite beneficial. DES and LCA integration is a unique combination for analysing the cause and effect of various scenarios in which time, resources, place, and randomness of input variables affect the outcome (Johansson et al., 2009). DES is able to model and represent not only the production system variables and patterns, but also the environmental aspects of those systems (González, Yiu, et al., 2012). The DES approach is able to integrate environmental loads of different life cycle phases of a construction product in only one process model. Therefore, it is not only a proper tool to improve current LCA data of complex and dynamic construction operations, but also to quantify the environmental impacts of an entire construction product. In addition, to consider the environmental impacts of a process, it is important that the environmental parameters and the process parameters are assessed simultaneously in the same simulation model (González & Echaveguren, 2012). This simultaneous assessment is possible through the integration of DES and LCA. Moreover, the production systems in construction have a nature that involves a large number of variables and processes, complex and dynamic relationships between parties and stages, high levels of uncertainty, among other factors (González et al., 2009). Thus, DES could be more beneficial while integrated to LCA in construction.

BACKGROUND

Different studies have revealed positive effects on evaluation of environmental metrics while integrating DES and LCA (Andersson et al., 2012). It has been proposed that DES can complement conventional tools, such as LCA, used for sustainable design and manufacturing strategies, specifically in investigating recycling strategies for plastic wastes (Rios et al., 2003). Wohlgemuth et al. (2006) introduced environmental considerations into the DES modelling of manufacturing systems. They developed a method to merge a methodology related to LCA (i.e., material flow simulation) with DES, to include both economic (e.g., bottlenecks detection, maintenance planning, and machine acquisition) and ecological factors (e.g., emissions, raw material, and energy consumption), and applied the method to modelling a semiconductor lithography process. The same method was applied in a study of engine manufacturing that provided deeper understanding on the relationship between electricity and material usage and identified energy saving potentials (Reinhard et al., 2007). Solding et al. (2006) and Solding et al. (2005) used DES to find out energy bottlenecks in foundries in order to reduce environmental impacts of energy consumption. Persson et al. (2007), Alvemark et al. (2007) and Ingvarsson et al. (2006), used DES as a tool for environmental measurements in food production. The integration of DES and LCA was used in the model developed by Huang et al. (2007) to predict the long term environmental consequences of different urban water management strategies. Johansson et al. (2008) combined DES with LCA to improve a juice manufacturing system. Heilala et al. (2008) presented this LCA perspective to the DES community as part of a combined tool to assess the automation level, ergonomics, and environment of a manufacturing system. In another study, LCA was combined with DES to assess the environmental impact of diapers (Guidosh, 2009); in this case, an existing standard LCA model was translated into the DES environment. Löfgren et al. (2011) described how DES can be extended by combining it with LCA to measure, in detail, the environmental performance of a company's manufacturing system.

In construction, DES modelling has been given a significant amount of attention, and during the last three decades, researchers have developed several simulation tools and engines to model and optimize construction operations (Halpin, 1976; Ioannou, 1989; Martínez, 1996; Marzouk et al., 2003; Shi et al., 1997). However, the study of project's environmental effects has not received yet much attention in construction, except for some recent studies that have focused on the analysis of emissions in construction projects using DES modelling techniques and environmental models (Ahn et al., 2009; Ahn, Pan, et al., 2010; Ahn, Xie, et al., 2010; González & Echaveguren, 2012). One interesting finding provided by these studies was the demonstration that emission estimates using the traditional LCA approach or the integration of emission models and standard bills of materials can be improved with DES techniques (González & Echaveguren, 2012). However, this integration has not yet been applied for environmental analysis of an entire construction product.

AIM, SCOPE AND METHODOLOGY

The aim of this research is to simultaneously assess production variables and environmental performance over time through the integration of DES and LCA. In other words, it should validate that DES is able to simultaneously optimise production variables such as time and cost; and environmental variables such as energy and emission in the same simulation model. The scope of this research is limited to the construction phase; however, the DES approach is able to integrate environmental loads of different life cycle phases of a construction product in only one process model. ExtendSim v8 as a DES modeling software was selected to model the project operations due to its powerful features to visualize and handle highly dynamic and complex systems (ExtendSim v8 User Guide, 2010). Required LCA data including fuel consumption of machineries and equivalent amount of carbon emission were obtained from online databases and linked to the DES model. As an example, depending on type and model, a loader consumes up to 0.4 litres diesel fuel per kilometer in normal condition while each litre of diesel fuel emits 2.7 kg CO_2 eq. (Guidance for Voluntary Corporate Greenhouse Gas Reporting, 2011). The integration was implemented on an earthmoving operations case study. The case study model has then been verified and validated based on real project data to ensure that the model both matches to the modeller's understanding of the system and the real project. If a model has been verified, validation seeks to determine whether the modeller truly understood the real system. This step was performed with the participation of project personnel who are quite familiar with the earthmoving operations. 100 simulation runs were then developed for each experimental scenario to assure estimates with a 95% confidence interval and a relative error of less than 5% (Law, 2007). Low standard deviation of the variables proved that an average would be the most proper result for simulation output analysis.

SPECIFICATIONS OF THE CASE STUDY MODEL

Foundation (10*10*3) construction of three 40-45 meter telecommunication masts (MTN-Irancell project in Iran) has been considered as the case study. Movement of machineries were modeled in ExtendSim with the aim of optimizing both environmental and production variables. Excavation process (P1) in the first site (S1), second site (S2) and third site (S3) include moving of trucks from the truck parking site to each of the sites (T Move), filling of trucks by the loaders available onsite (L/T Excavate), hauling the excavated material to the dumping site (T Haul), the dumping operation itself (T Dump) and finally returning back to the truck parking site (T Return). While the P1 operations are finished at S1, S2 and S3, concrete pouring process (P2) starts with filling mixers at the batching (M Fill), followed by hauling the concrete to the sites (M Haul), dumping concrete to fill the excavated volume (M Dump) and returning back to the batching (M Return).

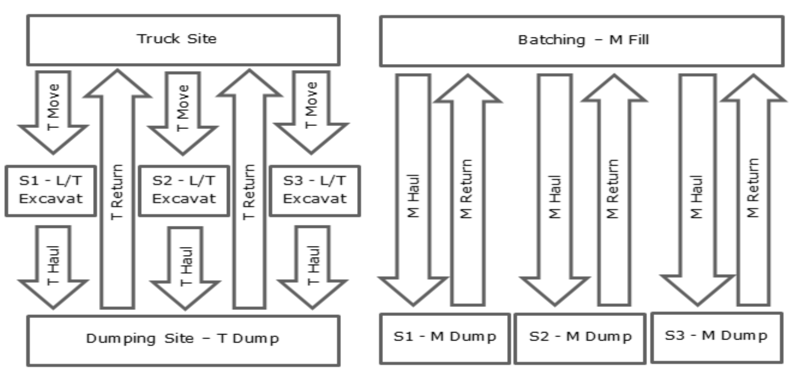


Figure 1– P1 and P2 earthmoving operations (movement of machineries in the base model)

Regarding the modeling purpose (movement of machineries), bar bending process is not considered in the model. Based on project cost data, hiring costs of machineries have been considered 10$/hr, 15$/hr and 25$/hr for trucks, mixers and loaders respectively. The diesel fuel cost was also considered 0.8$/lit in this project. The model calculates Fuel Cost (FC) and Hiring Cost (HC) of machineries separately for each of the operations based on the Working Time (WT) of machineries and Process Time (PT) of both P1 and P2 at all sites. The total cost is calculated by adding up the fuel cost and hiring cost of machineries. Required data including duration of operations were obtained from interview with experts who are intimately familiar with the project operations. Regarding the modeling purpose, a triangular distribution has been considered for the duration data. Fuel Consumption (Fu Co) and Carbon Emission (Co Em) are calculated based on distances, duration of operations and the LCA data linked to the model.

Table 1 – Distance, duration, fuel consumption and carbon emission of the project operations (base model)

Activity	Distance (km)	Triangular Distribution (min) Min.	Max.	Mode	Fuel Consumption lit/km	lit/hr	Carbon Emission kg/km	kg/hr
T Move	24	24	72	43	0.25	−	0.675	−
	13	13	39	23.5	0.25	−	0.675	−
	12	12	36	21	0.25	−	0.675	−
L/T Excavate	−	6	13	10	−	L: 9.5	−	L: 25.65
					−	T: 5	−	T: 13.5
T Haul	39	39	117	69.5	0.25	−	0.675	−
	14	14	42	25	0.25	−	0.675	−
	28	28	84	50	0.25	−	0.675	−
T Dump	−	1	3	2	−	5	−	13.5
T Return	14	14	43	26	0.25	−	0.675	−
M Fill	−	5	15	11.5	−	6	−	16.2
M Haul & M Return	4.5	4.5	13.5	8	0.3	−	0.81	−
	15	15	45	27	0.3	−	0.81	−
	10.5	10.5	31.5	19	0.3	−	0.81	−
M Dump	−	10	20	16.5	−	6	−	16.2

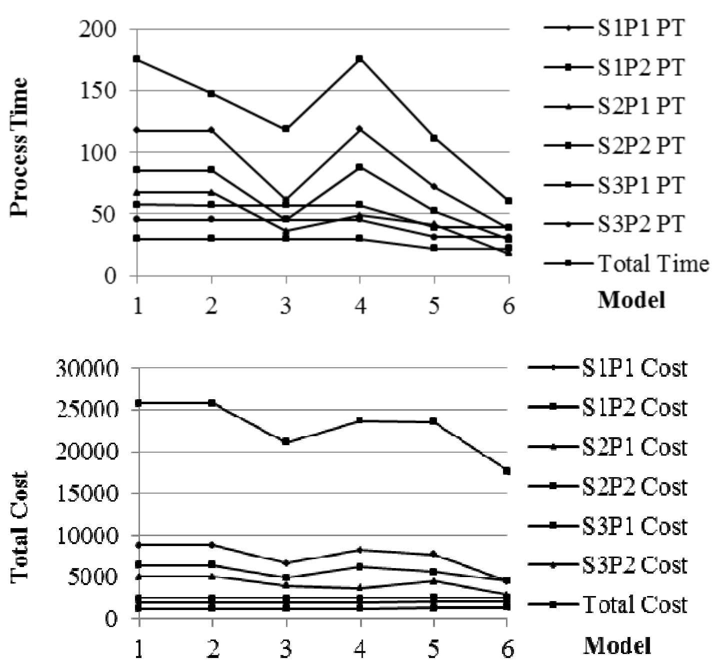
IMPROVEMENT MODELS – EXPERIMENTAL SCENARIOS

Several experimental scenarios have been implemented on the base model with the aim of improving the earthmoving operations. Improvements are based on both experts' and authors' opinions. Removing non-value-adding activities or waste from the earthmoving operations has been the main concern for building the improvement models. It enables authors to demonstrate simultaneous monitoring and control of environmental and production variables over time and consequently propose an approximate optimisation approach based on all variables involved. As a result, next section of the paper proposes a comparative study of environmental and production variables and discusses the improvements achieved. The analyses are based on the simulation output of the following six models: (1) As-built model of the project (base model) is considered as the first model. (2) Total project time of the second model is reduced by starting P2 immediately after P1 is finished in each of the sites, rather than starting P2 after P1 is completely finished in all sites. Reducing the batch size (excavation volume) is another improvement of the second model. In such a case, depending on the excavation volume and the process times, total project time is reduced by starting P2 before P1 is finished in each of the sites. (3) Reducing construction process waste in transportation is achieved in the third model by doubling the truck capacity from $5m^3$ to $10m^3$. The hiring cost is also doubled with respective changes on duration of truck filling process, fuel cost, fuel consumption and carbon emission. The effect of double truck capacity on both environmental and production variables are discussed based on the results of this model. (4) Similar to the third model, construction process waste in transportation is reduced in the fourth model through certain changes on truck routing. In this case, trucks return to sites immediately after the dumping process is finished. The "T Move" operation is omitted and respective changes on distances and durations are applied. (5)

Approximated optimization of number of machineries based on trial and error method forms the sixth model. Several models were tested to approximately optimize the number of trucks, loaders and mixers to reduce time, cost, fuel consumption and carbon emission. Both environmental and production variables were involved in this approach. The number of trucks and mixers are increased from 3 and 2 to 5 and 3 respectively. The number of loaders remained 1 in each of the sites. Improvements achieved are discussed based on the results of the fifth model. (6) All improvements are applied together in the sixth model to demonstrate the total potentiality.

RESULTS AND DISCUSSIONS

Figure 2 shows that improvements of the second model reduce the total project time by 27.56 hours (174.96-147.40) while do not affect the total cost of machineries. The improvements do not affect the environmental variables as well. Based on the results of the third and fourth models, reducing construction process waste in transportation significantly affects both environmental and production variables. The third model saves 56.32 hours on total time (174.96-118.64), 4668.22$ on total cost (25773.06-21104.84), 2430.27 liters on total fuel consumption (8658.33-6228.06) and 6561.71 kg eq. on total CO_2 emission (23377.48-16815.77); while the fourth model doesn't affect the total project time but saves 2108.71$ on total cost (25773.06-23664.35), 1621.45 liters on total fuel consumption (8658.33-7036.88) and 4377.91 kg eq. on total CO_2 emission (23377.48-18999.57). In the third model, truck capacity and hiring cost both increased to double with respective changes on duration of truck filling process, fuel cost, fuel consumption and carbon emission. However, the third model affects both environmental and production variables more than the fourth. The result of the fifth model illustrates that optimisation of number of machineries considerably affects production variables but not environmental. It saves 63.85 hours on total project time (174.96-111.11) and 2239.18$ on total cost of machineries (25773.06-23533.88). Based on the result of the sixth model, applying improvements in one model significantly reduces time, cost, fuel consumption and carbon emission in the project. Generally, improvements applied to this case study, reduced total project time by 66% (1-60.69/174.96), total cost of machineries by 32% (1-17666.57/25773.06), total fuel consumption by 39% (1-5238.47/8658.33) and total CO_2 emission by 40% (1-14143.88/23377.48).



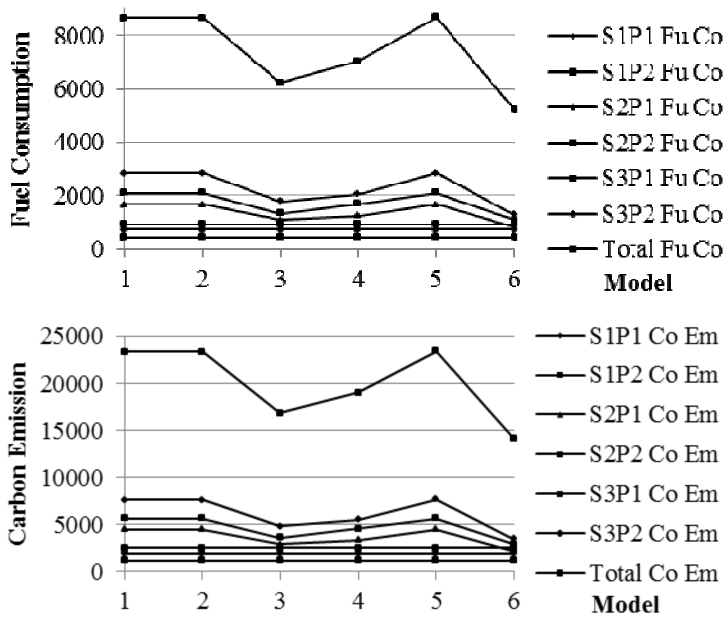
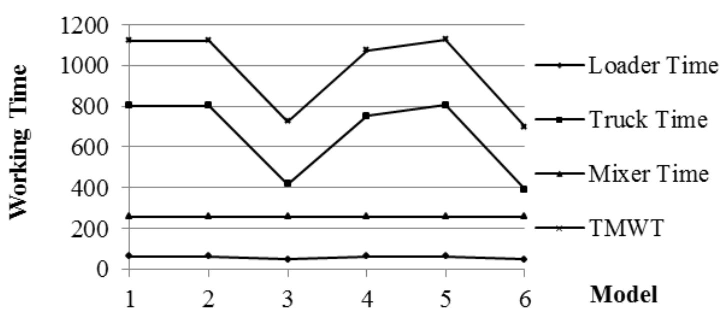


Figure 2 – P1 and P2 environmental and production variables of site 1, 2 and 3 (models 1-6)

Comparing results of the first and second models on figure 3 confirms that although improvements of the second model including reduction of the batch size (excavation volume) reduce the total project time, they do not influence the total machineries working time. Total Machineries Fuel Cost (TMFC), Total Fuel Consumption (Total Fu Co) and Total Carbon Emission (Total Ca Em) have remained constant in the second model as well. The third and fourth models which reduce construction process waste in transportation approve the idea that major savings on time, cost, fuel consumption and carbon emission are based on reducing movement of trucks rather than mixers or loaders. The third and fourth models save 398.24 (1123.43-725.19) and 48.66 (1123.43-1074.77) hours on total time, 1944.21$ (6926.66-4982.45) and 1297.16$ (6926.66-5629.50) on total cost, 2430.27 (8658.33-6228.06) and 1621.45 (8658.33-7036.88) liters on total fuel consumption and 6561.71 (23377.48-16815.77) and 4377.91 (23377.48-18999.57) kg eq. on total CO_2 emission respectively. Optimisation of number of machineries shows no improvement on time, cost, fuel consumption and carbon emission based on the results obtained from the fifth model. The reason relies on the fact that optimisation of number of machineries affect the process time and hiring cost not working time and fuel cost. Generally, improvements applied to this project, reduced total machineries working time by 38% (1-698.25/1123.43), total machineries fuel cost by 40% (1-4190.78/6926.66), total fuel consumption by 39% (1-5238.47/8658.33) and total carbon emission by 40% (1-14143.88/23377.48). Utilisation rate of machineries based on the project's operations are summarized in the appendix.



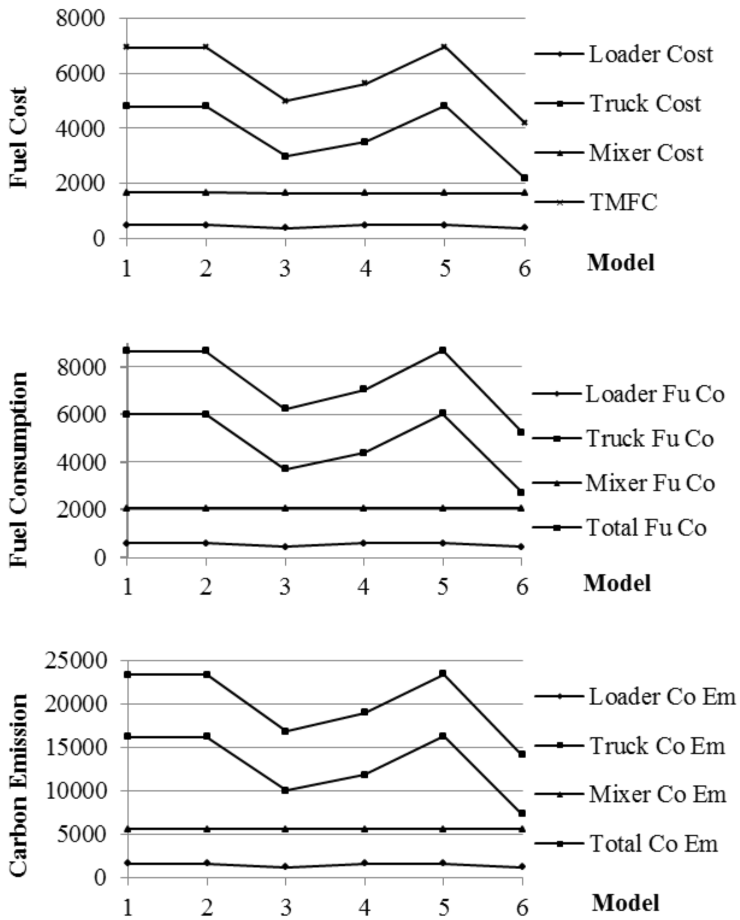


Figure 3 – Construction machineries' environmental and production variables (models 1-6)

CONCLUSION AND FUTURE RESEARCH POTENTIAL

This study proposed a new methodology for simultaneous monitoring and control of environmental and production variables in earthmoving operations through the integration of DES and LCA. Results affirmed the great potentiality in reducing time, cost, energy consumption and carbon emission. Applying such environmental analyses to all kinds of earthmoving operations, contributes to the development of more sustainable road construction projects considering environmental aspects in the planning phase or even during the construction phase. The authors are developing a generic model capable of analyzing environmental impacts of road construction operations through the integration of DES and LCA. The model is expected to be linked to Life Cycle Inventory (LCI) database to record associated environmental inputs and outputs; Life Cycle Impact Assessment (LCIA) database to evaluate associated impacts on environment; and Life Cycle Costing (LCC) data to consider imposed environmental costs. Besides, this research has the potential to propose a decision support tool by formulating a multi-objective optimization approach applying artificial intelligence principles, in which environmental and production variables are simultaneously optimized in the same simulation model. This paper is part of an on-going research.

APPENDIX

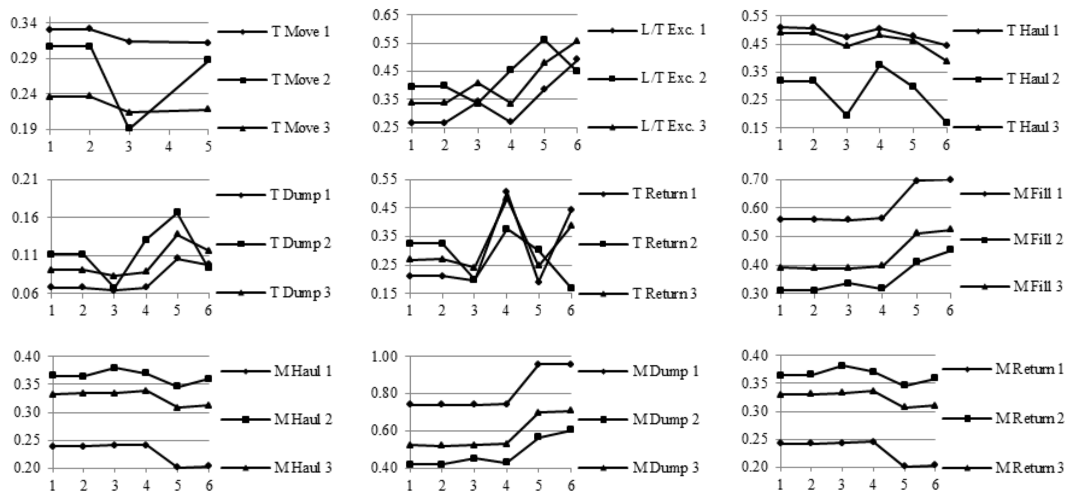


Figure 4 – Utilisation rate of machineries based on the project's operations (models 1-6)

REFERENCES

Ahn, C., Martinez, J. C., Rekapalli, P. V., & Peña-Mora, F. A. (2009). Sustainability analysis of earthmoving operations. Paper presented at the Simulation Conference (WSC), Proceedings of the 2009 Winter.

Ahn, C., Pan, W., Lee, S. H., & Peña-Mora, F. (2010). Enhanced estimation of air emissions from construction operations based on discrete-event simulation. Paper presented at the Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE) 2010.

Ahn, C., Xie, H., Lee, S. H., Abourizk, S., & Pena-Mora, F. (2010). Carbon footprints analysis for tunnel construction processes in the preplanning phase using collaborative simulation. Paper presented at the Proceedings of the Construction Research Congress 2010.

Alvemark, O., & Persson, F. (2007). Flow simulation of food production; cultured dairy products: M. Sc. Thesis, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden.

Andersson, J., Johansson, B., Berglund, J., & Skoogh, A. (2012). Framework for ecolabeling using discrete event simulation.

ExtendSim v8 User Guide. (2010). Imagine That Inc.

González, V., Alarcón, L., & Molenaar, K. (2009). Multiobjective design of Work-In-Process buffer for scheduling repetitive building projects. Automation in Construction, 18(2), 95-108.

González, V., & Echaveguren, T. (2012). Exploring the environmental modeling of road construction operations using discrete-event simulation. Automation in Construction, 24, 100-110.

González, V., Yiu, T. W., & Martinez, P. (2012). Towards a dynamic modelling framework for assessing the sustainable degree of construction materials. Paper presented at the 37th Annual Conference of the Australasian Universities Building Educators Association (AUBEA), Sydney, Australia.

Guidance for Voluntary Corporate Greenhouse Gas Reporting. (2011). Wellington, New Zealand: Ministry for the Environment.

Guidosh, J. A. (2009). The use of Life Cycle Assessment through an Objective Framework Constructed by Simulation. (Youngstown State University).

Halpin, D. W. (1976). CYCLONE: Methods for modelling job site processes. Journal of Construction Division, 103(3), 489 – 499.

Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B., & Stahre, J. (2008). Simulation-based sustainable manufacturing system design.

Huang, D. B., Scholz, R. W., Gujer, W., Chitwood, D. E., Loukopoulos, P., Schertenleib, R., & Siegrist, H. (2007). Discrete event simulation for exploring strategies: An urban water management case. Environmental science & technology, 41(3), 915-921.

Ingvarsson, A., & Johansson, C. (2006). Flow simulation of food industry production: ingemar johansson i sverige AB (In Swedish): M.Sc. Thesis, Department of Product and Production Development, Chalmers University of Technology.

Ioannou, P. (1989). UM-CYCLONE reference manual. Tech. Report. UMCE-89-11, Dept. of Civ. Engrg., University of Michigan, Ann Arbor, Mich.

Jensen, A. A., Hoffman, L., Møller, B., Schmidt, A., Christiansen, K., Elkington, J., & van Dijk, F. (1998). Life cycle assessment (LCA): a guide to approaches, experiences and information sources: European Environment Agency.

Johansson, B., Skoogh, A., Mani, M., & Leong, S. (2009). Discrete event simulation to generate requirements specification for sustainable manufacturing systems design.

Johansson, B., Stahre, J., Berlin, J., Östergren, K., Sundström, B., & Tillman, A. M. (2008). Discrete Event Simulation With Lifecycle Assessment Data At A Juice Manufacturing System.

Law, A. M. (2007). Simulation modeling and analysis / Averill M. Law: Boston : McGraw-Hill, 2007 (2006 printing).

Lind, S., Johansson, B., Stahre, S., Berlin, C., Fath, A., Heilala, J., Helin, K., Kiviranta, S., Krassi, B., & Montonen, J. (2009). SIMTER–A Joint Simulation Tool for Production Development. VTT Working Paper 125. 49 p. Espoo.

Löfgren, B., & Tillman, A. M. (2011). Relating manufacturing system configuration to life-cycle environmental performance: discrete-event simulation supplemented with LCA. Journal of Cleaner Production.

Martinez, J. C. (2010). Methodology for conducting discrete-event simulation studies in construction engineering and management. Journal of Construction Engineering and Management, 136, 3.

Martínez, J. C. (1996). STROBOSCOPE: State and resource based simulation of construction processes: University of Michigan.

Marzouk, M., & Moselhi, O. (2003). Object-oriented simulation model for earthmoving operations. Journal of construction engineering and management, 129(2), 173-181.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. Ecological Economics, 60(3), 498-508.

Persson, D., & Karlsson, J. (2007). Flow simulation of food industry production: kiviks musteri AB (In Swedish): MSc Thesis, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden.

Reinhard, J., & Motsch, S. (2007). Material Flow Management in a Motor Fabrication: Identifying Saving Potential in the Mechanical Production by Modeling Energy-and Material Flows as Well as Machine Time Using Umberto. Information Technologies in Environmental Engineering, 409-415.

Reuter, M., & Van Schaik, A. (2004). Optimization of the Resource Cycle: Linking Research and Teaching in Recycling at the Delft University of Technology. Paper presented at the International Conference on Engineering Education in Sustainable Development, Barcelona, Spain.

Rios, P., Stuart, J. A., & Grant, E. (2003). Plastics disassembly versus bulk recycling: Engineering design for end-of-life electronics resource recovery. Environmental science & technology, 37(23), 5463-5470.

Shi, J., & AbouRizk, S. M. (1997). Resource-based modeling for construction simulation. Journal of construction engineering and management, 123(1), 26-33.

Solding, P., & Petku, D. (2005). Applying energy aspects on simulation of energy-intensive production systems.

Solding, P., & Thollander, P. (2006). Increased energy efficiency in a Swedish iron foundry through use of discrete event simulation.

Wohlgemuth, V., Page, B., & Kreutzer, W. (2006). Combining discrete event simulation and material flow analysis in a component-based approach to industrial environmental protection. Environmental Modelling & Software, 21(11), 1607-1617.