A DISTRIBUTED SIMULATION APPROACH FOR PROJECT LOGISTICS, MANAGEMENT, AND CONTROL

Romeo Bandinelli
Dipartimento di Energetica “Sergio Stecco”
Università di Firenze
romeo.bandinelli@siti.de.unifi.it

Alessandra Orsoni
School of Business Information Management
Kingston University
KT2 7LB, Kingston upon Thames, UK
a.orsoni@kingston.ac.uk

KEYWORDS

Project Logistics, Project Management and Control, Concurrent Engineering, Distributed Simulation.

ABSTRACT

This paper proposes a distributed simulation approach to address the logistic implications of design and assess their impact on performance during project execution. Relevant areas of application include large construction projects involving the installation of multiple systems and, simultaneously, the interests of multiple parties. Individual models of the installation activities pertaining to each system are built using commercial simulation packages. These models are then linked using the Java RMI® (Remote Method Invocation) standard to provide global measures of project performance for both local and central design decisions. Several uses of this simulation approach can be identified during the different phases of the project life-cycle, for instance to test alternative solutions during the conceptual design phase or to accommodate late design changes with minimal disruptions to the project schedule and budget.

INTRODUCTION

Distributed simulation has been widely used outside the original military context to address important production and management problems related to the supply chain. This paper extends the use of distributed simulation from mass/batch production to large one-off projects. Examples of suitable projects include for instance the construction of large industrial and occupied facilities. Because such projects involve the interests of multiple parties, it is of the highest importance that any design decisions made either centrally (i.e. at the owner’s or at the general contractor’s level) or locally (i.e. at the sub-contractor’s level) are assessed and discussed using common metrics [1,2]. This ensures that the logistic and performance implications of the relevant design specification are fully understood and appreciated prior to their full-scale implementation. Specifically, the simulation approach aims to establish unbiased criteria and measures for the evaluation of decision alternatives to bridge the gaps among the objectives of the different project stakeholders. By these means distributed simulation supports the application of a concurrent engineering approach as potential issues in the project logistics, management, and control can be anticipated and addressed since the early stages of design.

BACKGROUND

The work presented in this paper builds upon prior research on the performance of complex large-scale projects [3,4]. Modelling and simulation techniques, in the form of dynamic process simulation models, were designed to assess the performance implications of change in the presence of inter-system process dependencies. The initial solution worked as a single application package and was meant for the use of the general contractor to evaluate how changes introduced in the design and/or in the construction means or methods could influence project performance, as measured for instance by project duration and cost [3,4]. The implemented simulation tool consisted of a library of system and material specific modules, each one representing the detailed installation/construction activities for a particular system.

Since the early applications of the tool it was observed that each system and material and specific model is better maintained and customised at the sub-contractor’s site: the detailed specifications of possible changes are usually implemented directly by the sub-contractors, who are also free to choose the construction means and methods as long as they are able to meet the specified completion deadlines. Based on such considerations, a natural extension of the work involved the realisation of a network of independent system and material specific models based on the Java RMI® (Remote Method Invocation) standard. The paper will discuss the relevant features of the network and will present the results of a case study based on an actual construction project.

SIMULATION APPROACH

As illustrated in the previous section, a prototype simulation tool was first developed in the SIMPROCESS® environment as a library of system and material specific modules, which enabled the definition of a project by simply dragging-and-dropping the relevant modules. For the purposes of this research the existing modules were extracted and readapted to serve as simulation federates in the distributed architecture. Special attention was devoted the definition of appropriate variables tracking federation-wide the local

Proceedings 16th European Simulation Symposium
György Lipovszki, István Molnár © SCS Press, 2004
ISBN 1-56555-286-5(book) / ISBN 1-84233-106-x(CD)

progress for the individual systems to ensure that the next installation phases could be scheduled and executed without introducing simulation delays. This is especially important when dealing with the representation of multiple interdependent processes, where technical logical, regulatory and resources constraints tie the relative production rates among the systems. Specifically, the completion of one installation process in a particular zone of the facility, allows for the next crew to start their job in that same zone. If the completion of the previous job is not effectively communicated, the installation process for the next system may be delayed in a way that is not representative of the reality of the process.

The bulit-in capabilities of SIMPROCESS®, which enable the adoption of the RMI standard greatly simplify the realisation of a network and overcome several of the problems related to the timing of simulation synchronisation. Recent research by the authors has focused on the timing of federation synchronisation, when adopting the “next event” approach within the HLA-RTI standard [5,6]. In such applications it is critical that the frequency of communications among simulators is as reflective as possible of the process characteristics so as to minimise the waste of simulation time caused by the occurrence of asynchronous events.

With the RMI-based approach to distributed simulation, the timing of communication is no longer a problem. A detailed description of the RMI features and functionalities can be found in the relevant website [http://java.sun.com/products/jdk/rmi/]. In synthesis, RMI® enables the programmer to create distributed Java technology-based applications, in which the methods of remote Java objects can be invoked from other Java virtual machines, possibly on different hosts. A Java program can make a call on a remote object once it obtains a reference to the remote object itself, either by looking up the remote object in the bootstrap naming service provided by RMI or by receiving the reference to it as an argument or a return value. A client can call a remote object in a server, and that server can also be a client of other remote objects. RMI uses object serialisation to marshal and unmarshal parameters and supports true object-oriented polymorphism.

Since the study represented a first application of the distributed approach to the analysis of the logistic implications of early design decisions in the performance of large projects, significant effort was devoted to the validation of both the individual models and the federation as a whole. The validation of the individual models was highly supported by the availability of historical data from previous projects that enabled cross-checking and validation of the simulated time and performance estimates. The availability of data from past projects allowed for the analogical validation of the entire federation as well, by comparing the performance measures obtained, such as duration and costs, to their actual values. In effects, project managers typically refer to previous projects to estimate the duration and costs for each aggregate project phase and during project execution they record the actual values for project control purposes. It is important to observe that by looking at processes at the aggregate level (e.g. installation of electrical wiring on the second level, or installation of plumbing fixtures in zone A) it is only possible to derive rough estimates for the start/end dates of each phase. The representation of the logistic implications of design and methods during project execution is far more detailed in the simulation because inter-system process links build their effects at the detailed task and component level and these links cannot be captured by looking at processes at the aggregate level.

ASSESSING THE PERFORMANCE OF DESIGN-DRIVEN LOGISTIC CHANGES

The introduction of design and technological changes impacts the logistics of project execution at three levels: the system, the inter-system, and the whole project level. Specifically, the system level observes the logistic implications of change within the system of introduction. The inter-system level tracks how their secondary effects influence the installation of other facility systems. The whole project level observes their impact on the performance of the overall project. Prior research, based on extensive simulated scenario testing, has demonstrated that the impact of change can be accurately tracked at all three levels, across multiple dimensions of performance [3,4].

Previous studies have shown that the performance of large construction projects is multi-attribute[3,4]. Because the interests of multiple parties are simultaneously involved (e.g. the owner’s, the general contractor’s and the different specialty contractors’), depending on the particular project and party of perspective, one aspect of performance may appear more important than others towards the success of the project. However, in general, the level of success achieved in a project can only be measured across multiple dimensions of performance [7,8]. Based on these considerations, and on previous testing of the individual models as stand-alone applications, a number of performance measures were selected as suitable indicators of project performance. These include project duration, duration-based cost, cost of utilised resources, percentage resources utilisation, and index of workers’ exposure to dangerous conditions (danger index). Specifically, the duration-based cost represents the total cost of the project, assuming that all resources are present on the construction site for the entire duration of their scope of activity within the project. The cost of utilized resources represents the cost of performing project activities and tasks, excluding resource costs of delays and wait times introduced by process interdependencies. The percentage of resource utilization is the ratio of these two costs. Worker exposure to dangerous condition is measured through an index that builds upon tabulated values of occurrence of injuries during the performance of specific construction tasks [9,10] over the entire duration of the project.

It is important to observe that the choice of performance measures targets the assessment of the impact of inter-system process dependencies. Measures such as duration and duration-based cost in fact are “dynamic” measures of performance, meaning that they account for the actuality of the duration and cost of the construction process because they reflect inter-system process dynamics. Measures of performance such as cost of utilized resources and workers exposure to dangerous conditions, are not dynamic in such a sense. They are direct functions of the number of man hours required to complete the project and do not account for the resource idle time determined by inter-system process dynamics. Any discrepancies in the simulated results for these two sets of performance measures is entirely explained by the effects of inter-system process links.

EXAMPLE ANALYSIS

In order to assess the benefits that may be accrued from the application of the implemented federation architecture to the study of complex projects, an example analysis was performed based on data from an actual construction project. The project involved the realization of a research facility for a large pharmaceutical company, to accommodate both laboratories and office spaces. The study involved the evaluation of design alternatives for the main service systems included in the facility: the electrical and communication systems, the plumbing and fire protection systems, and the heating and ventilation systems. As part of this case study, the simulation tool was used to compare the performance of two pairs of design alternatives during project execution. The first analysis focused on layout alternatives and compared the performance of the centralised and decentralised layout options. The second one focused on system alternatives and compared the performance of air-based versus water based heating.

For the purposes of this analysis the federation had to be customised to accommodate and track the relevant changes in project logistics induced by each design alternative. Typical changes in project logistics are related to changes in the bill of materials for the related sub-systems and to their spatial distribution in the facility. The logistic implications of these changes include the introduction of additional accessibility constraints, which influence the spatial and temporal allocation of crews to different jobs and the cross-system sequencing of installation activities. These combined effects influence the relative production rates among the systems and thereby generate an impact on the overall project performance. Changes in the bill of materials for a particular sub-system involve changes in the input data for each federate, however their impact on project performance is tracked at the federation level by observing the corresponding changes in the relative installation rates among the systems. Progress is especially difficult to track among different systems because different systems use different spatial units of progress. For instance structural systems use bays, enclosure systems may refer to zones or levels, interior finishing can be tracked by room, and services may be tracked by riser/feeder group, by level, or by zone, depending on the specified facility layout.

CENTRALISED VS. DECENTRALISED LAYOUT

Design changes in the system layout, particularly centralisation versus decentralisation of the vertical risers, were analysed with respect to the overall layout of the water-based service systems (i.e. plumbing, heating and fire protection). Centralising the layout means shifting from a primarily vertical layout, with a number of vertical risers close to the number of usage points, to a largely horizontal layout, where few risers feed the usage points through a long network of horizontal pipes on each level.

Not only does this shift represents a significant design change in terms of number and type of units to be installed, but it also introduces an additional logistic constraint that links the installation processes of the fire protection and plumbing systems. This constraint, driven by spatial and accessibility requirements, ties the rate of installation of the horizontal pipes for the two systems, because the two need to run parallel on the different facility levels and share the same supporting trays.

Moving from a decentralized to a centralized layout has important impacts at the federation control level. The progress status for the installation of the plumbing pipes needs to be tracked at the federation level, and synchronisation events need to be tailored to account for their expected installation time, so that the fire protection units can be timely released for installation on that level.

Changes in layout have no impact on the structure of the individual system federates. The modules are system and material specific, and thus independent of the particular system size and layout. Changes in the number of units to be installed do not influence the type of activities to be performed and, thus, are only reflected in the input quantities (i.e. bill of materials).

The relative changes in project performance are displayed in figure 1. The effects of centralisation measured at the whole project level include major increases in overall project duration (57%) and in duration-based cost (36%). In addition, it is now the installation of the fire protection system, instead of the electrical system, that drives the duration and overall cost of the project. The change in design (number and type of units to be installed) actually reduces the cost of utilised resources, both at the system and at the whole project level, but also introduces changes in the inter-system installation rates, which impact the overall progress rate and project duration. The combined impact of these two effects is a reduction of resource utilisation (i.e. the cost of utilized resources divided by the duration-based cost) equal to 32%.

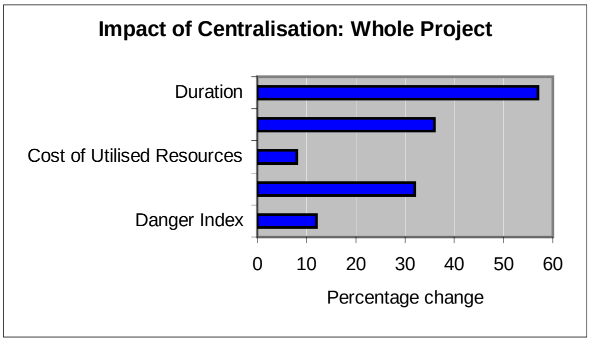

Figure 1: Performance Impact at the Project Level

One of the benefits of a distributed approach in the study of change is the possibility of analysing performance at the system level by looking at the outcomes of each individual federate, when run in the context of the whole federation. In most cases the analysis of the federation outcomes at the system level produces results that are quite far from the expected and can only be explained as the result of inter-system process dependencies. For instance, in this scenario, no change was introduced in the design of the electrical system, which for this project application was fairly centralised to begin with, therefore both the cost of utilised resources and the danger index, which are system specific measures, do not change. However, a decrease in duration-based cost is observed which in turn leads to an increase of resources utilisation. The decrease in duration-based cost for the electrical system is explained in terms of inter-system process links, which constrain the spatial progress on the installation of the heating system to depend on the rate of installation of the heating system.

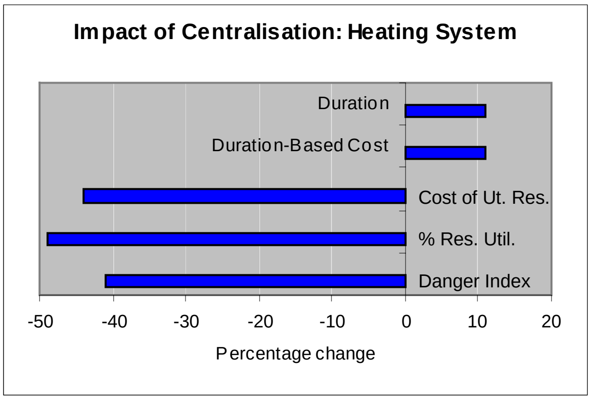

Figure 2: Performance Impact at the System Level

Because the shift to a centralised layout for the heating system makes its installation faster, performance benefits can be observed in the installation of the electrical system due to a reduction in resources idle time (resources are idle while waiting for the installation of the heating pipes in the next zone). Figures 2 and 3 summarise these performance outcomes at the system (heating system) and inter-system (electrical system) levels, respectively.

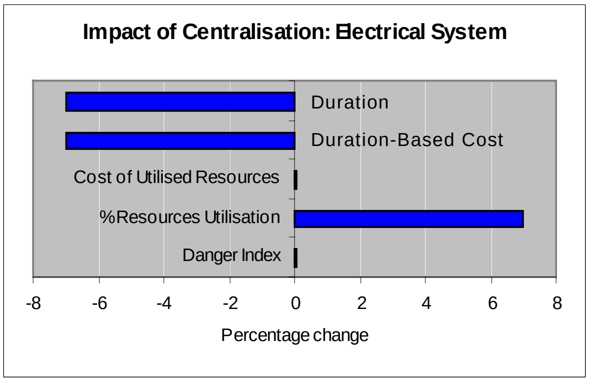

Figure 3: Performance Impact at the Inter-System Level

AIR-BASED VS. WATER-BASED HEATING

A comparison is made between a water-based and air-based heating solution for a same decentralised layout.
The shift from a water based to an air-based system represents a shift from a closed loop type of system, characterised by supply and return pipes, to an open loop type of system, characterised by supply ducts only. The most interesting aspect of this second case is that no significant impacts can be identified at the system level: the time required to install a given length of air ducts is actually longer than the time required to install an equal length of water pipes, however no return line is required in the air-based configuration. For this particular system size and layout, the effects compensate so as to produce negligible changes in the performance measures at the system level. However, important impacts can be observed at the intersystem level: the installation of the electrical system is faster and the associated costs are lower. This effect is mostly determined by the different rate of installation of both the vertical and the horizontal units in the air-based system, as compared to the water-based solution, which overall increases installation efficiency for the electrical system (shorter idle time of resources while waiting for the horizontal heating conduits to be placed). Increased efficiency in the installation of the electrical system has significant impacts on the project as a whole, since any reduction in completion time for the electrical system directly translates in an equivalent reduction in project duration, and consequently decreases project cost.

For the purposes of this comparison the simulation federate representing the installation process for the water-based heating system had to be substituted with the corresponding air-based one, because the installation activities are substantially different. However, no relevant changes had to be made at the federation control level, since the spatial constraint that links the installation progress of the electrical system to that of the heating system does not vary as the system type is changed (i.e. the air ducts still need to be in place on one level before the installation of electrical conduits and wiring can start on that same level).

As anticipated above, the impacts of this change in the nature of the heating system at the whole project level are a reduction in project duration (-7%) and a corresponding reduction in duration-based cost (-2%). Changes in the cost of utilised resources and in the danger index for the whole project are negligible. Only a slight increase in the percentage resource utilization can be observed (+3%). Figure 4 summarises the relative performance results at the whole project level.

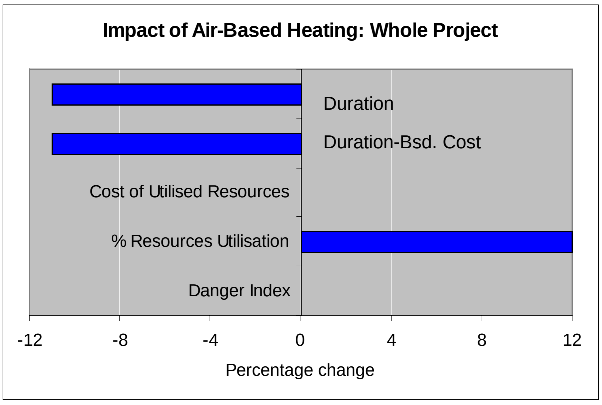

Figure 4: Performance Impact at the Project Level

At the system level, no significant impacts can be observed in the installation of the heating system. As explained at the beginning of this section this finding is rather coincidental, and results from the combination of two effects. The first one is that for this particular layout the total number of man-hours required to install the air-based and the water-based heating are approximately the same. The second one is that the activities required to install air ducts are characterised by the same level of danger as those required to install heating pipes.

At the inter-system level the installation of the electrical system is affected by the change in the type of heating system adopted. Duration and duration-based cost for the electrical system are both lower than the corresponding figures for the water-based heating alternative (-11% for both).

Since no change was introduced specifically in the electrical system itself, both the cost of utilised resources and the danger index remains the same in the two configurations, while the percentage of resource utilization increases (+12%), due to the decrease in installation time. Figure 5 summarises the relative performance results observed at the inter-system level

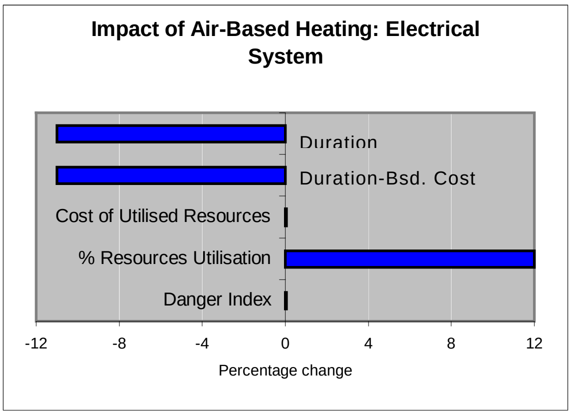

Figure 5: Performance Impact at the Inter-System Level

CONCLUSION

This paper has analysed the logistic implications of design changes during project execution and their impact on project performance. The analysis of change in complex construction projects requires a distributed simulation approach because many of the logistic implications of change can only be specified at the intersystem level, and only at this level they build their effects on project performance.

A distributed architecture is especially convenient because important construction projects involve multiple sub-contractors who are tied to specified completion deadlines but are otherwise free to choose their own construction means and methods. In this respect it is sensible to have them implement the customisation of their specialty federate models for the project and then observe their effects of their choices at the aggregate level by centrally running the federation. Design changes can be proposed and tested both locally, at the subcontractor’s level or centrally are the owner’s/general contractor’s level, but it is always necessary to test their effects on the performance of the project as a whole. Distributed simulation supports a concurrent engineering approach throughout the different phases of a project’s lifecycle, from the early design stages and feasibility studies to the later stage of project execution. The simulation-based methodology presented in the paper favours communication among the different project stakeholders and provides quantitative grounds for discussion before key design decision are made and implemented in an application context where full-scale experiments are financially too risky and time-consuming. The methodology also provides extensive support during project execution to better specify the logistics by which changes can be implemented at such late stages without compromising the existing project schedule and budget.

REFERENCES

[1] C.B. Tatum, Integrating Design and Construction to Improve Project Performance, *Project Management Journal, 21* (2), 1990, 35-42.

[2] J.T. O'Connor, & R.L. Tucker, Industrial Project Constructability Improvement, *ASCE Journal of Construction Engineering Management, 117*(2), 1986, 259-278.

[3] A. Orsoni, Assessment of organizational alternatives in complex large scale projects, *Proc. 2001 Summer Computer Simulation Conference (SCSC 2001),* Orlando, FL, 2001a, 611-616.

[4] A. Orsoni, Selecting the right technology: costs and benefits of dynamic multi-process simulation in complex, large-scale applications, *Proc. 5th World Multiconference on Systemics Cybernetics and Informatics (SCI 2001),* Orlando, FL, 2001b, 509-514.

[5] R. Bandinelli, M. Iacono, and A. Orsoni, Anticipating critical events to customise and improve the performance of federation runtime infrastructure, *Proc. 7th UKSim Conf., Oxford,* UK, 2004, 59-64.

[6] R. Bandinelli, M. Rapaccini, S. Terzi, & M. Macchi, Proposal for a framework for production plants remote control: a preliminary test case, *Proc. 15th ESS Conf., Delft*, NL, 2003, 343-348.

[7] C. Hendrickson, & R. Au, *Project Management for Construction* (Englewood Cliffs, New Jersey: Prentice Hall, 1989).

[8] F.W. Mueller, *Integrated Cost and Schedule Control for Construction* (New York, NY: Van Nostrand Reihnold Co, 1986).

[9] Occupational Health and Safety Administration. Construction accidents – the worker's compensation database 1985-1988. 1992. U. S. Department of Labor.

[10] Occupational Health and Safety Administration. Construction industry: OSHA safety and health standards. 1994. U. S. Department of Labor.

AUTHOR BIOGRAPHIES

ROMEO BANDINELLI received his laurea degree in Mechanical Engineering from the University of Florence in 2002 discussing the thesis "Remote Factory Control with Distributed Simulation". He is currently a PhD candidate in the Department of Energetic, Plants and Industrial Technologies at the University of Florence. His research interests include parallel and distributed simulation for industrial and supply chain applications, ICT, and business process re-enginering.

ALESSANDRA ORSONI is currently a senior lecturer in the School of Business Information Management at Kingston University (Kingston, UK). She received both her MS in Mechanical Engineering and her ScD in Engineering Systems Design and Innovation from the Massachusetts Institute of Technology (Cambridge, MA). Prior to joining Kingston University she was a research associate in the Department of Materials Science and Metallurgy at the University of Cambridge (Cambridge, UK) and worked as an assistant professor at in the Department of Production Engineering at the University of Genova (Genova, Italy). Her research interests include modelling, simulation, and AI techniques applied to the design and management of complex industrial systems.