A consideration of Boundary Objects as a means of Integrating Design and Construction – A Case Study

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Integration between Design and Construction is a common topic discussed in the literature in construction. The impacts of construction industry fragmentation are quite well known: poor design quality, lack of standards and constructability, suboptimal design solutions, high number of change orders, high rate of rework in design and construction, low value delivered for clients, design and construction delays and higher project costs. In the case of construction projects in which the design stage overlaps the construction stage, the industry fragmentation increases the projects' risks and in some cases it nullifies the gains in cost and time which come about when using the strategy of overlapping.

Although researchers tried to address the problem of industry fragmentation by implementing new tools and methods to integrate project stakeholders, for example, using Building Information Modelling (BIM), Integrated Concurrent Engineering, Big-Room, and so on, the literature is still lacking in concepts and theories about how to integrate planning and controlling of both Design and Construction stages.

The purpose of this paper is to present the use of some concepts, such as production batch and work package, in order to create a common ground among Design, Construction and Costs simulations using BIM and line of balance. The case study is a retrofit of a set of social housing in Antrim (Northern Ireland) which aims to improve the energy efficiency of solid wall houses, at the same time as reducing the disruption for end users. The study is part of the research

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project entitled S-IMPLER (Solid Wall Innovative Insulation and Monitoring Processes using Lean Energy Efficient Retrofit) funded by the Innovate UK, which aims to develop a retrofit solution for social housing built with solid walls to achieve 60% reduction in monitored energy costs, with less disruption for end users, keeping quality and safety at high levels.

The use of these concepts allowed the creation of different scenarios for design solutions and production system organization which were presented in a What-if Matrix. The costs changed as a consequence of the crossing scenarios. Adding to it, the definition of production batch and work package was essential to develop the BIM models (3D, 4D and 5D), as well as the line of balance used to plan the retrofit works and measure the end users disruption.

The research findings show that the common definition of production batch and work packages between Design and Construction stages used in the retrofit study worked as a boundary object in the development of BIM models and scenarios simulations. These concepts created the basis for the integration between design and construction, especially, in projects using BIM.

The results are not limited to the context of retrofit and further research is currently undertaken by the researchers to examine its validity and applicability in different settings.

Keywords: BIM; Line of Balance; integration design and construction

1. Introduction

Boundary objects are known in the construction industry as objects with mediating role to improve collaboration and generate common understanding among different social worlds. The term was introduced in 1989 by Star and Griesemer to describe the objects that “inhabit several intersecting social worlds and satisfy the informational requirements of each of them” (Star & Griesemer, 1989).

The idea of having boundary objects to integrate design and construction is not new. BIM models have been used as artefacts to satisfy informational requirements in both social worlds. Namely, in Forgues and Iordanova (2010) work, the authors describe BIM as a technology for innovation and knowledge generation in project process. However, there is no evidence in the lean management literature on how to structure design and construction using concepts of location breakdown structure as boundary objects. The common definition of some of these concepts can be applied for structuring the BIM models in order to simulate design and construction solutions.

This paper presents partial results of an ongoing doctoral research about planning and controlling integration for design and construction in projects where there is overlap between these phases. Specifically, the paper shows the first results of a project entitled S-IMPLER (Solid Wall Innovative Insulation and Monitoring Processes using Lean Energy Efficient Retrofit).

Some concepts used in the location breakdown structuring were used as boundary objects for the BIM models and line of balance development. The study findings highlight the importance of a common structure between design and construction as a means of integrating their decision making, as well their planning and controlling processes.

2. Case Study Description

S-IMPLER is a project which aims to develop a solution to the insulation of solid walls in the UK that is more cost effective than current solutions, with minimal occupant disruption and with 60% reduction in monitored energy costs (http://www.s-impler.com). The project is funded by Innovate UK and is a joint initiative between housing association, two small and medium enterprises, a contractor, academic institutions, a lean consultant, and a construction organization. The stakeholders have different roles in the project which is composed by nine work packages.

This paper presents the partial results of the BIM work package. The aim of this package is to develop a BIM based solution for the retrofit of solid wall housing using lean and collaborative improvement techniques. For it, five outcomes were developed: 1) 3D Models for design solutions and energy simulations; 2) 4D Models for simulating end users disruption during retrofit works; 3) 5D Models for cost estimation; 4) What-if Matrix of Scenarios; and 5) a BIM Retrofit Protocol supporting 'what if' scenarios for housing retrofits.

The Project is composed by 5 retrofit phases, with 4 improvement cycles between the phases. This paper reports the activities developed for the Phase 2 of the project.

3. Case Study Development

To begin the modelling process, the researcher defined the level of detail of 3D models according to the master schedule that was being studied for phase 2. The location breakdown structure of the houses was done, in combination with the retrofit work packages, their production batch size and crews. This information defined the level of detail of the BIM elements and the procedure was adopted in order to produce BIM models without excessive elements and data, and to have the same unit for simulations.

3D Modelling for Energy Savings Simulation

The process of 3D modelling started by the definition of possible solutions for each system that will be retrofitted in the houses: walls and roofs insulation; windows and doors; and, the heating system. The solutions for the external wall and roof insulation include two different products with different U-values. For windows and doors, also two products were choosing: double and triple glazed. The heating systems studied include a gas boiler system and a pellet furnace combined with solar panel. These solutions were combined to create three scenarios for energy consumption simulation. The outputs of these simulations were: total energy consumption per year; total CO_2 emission per year; and total cost. The results for each scenario were compared with the existing condition - see Table 1.

Table 1. Results of the energy consumption simulation for three scenarios.

	Scenario Pre-retrofit	Scenario 1	Improve-ment	Scenario 2	Improve-ment	Scenario 3	Improve-ment
Total Energy Consumption (kWh/a)	37662	33503	**11.04%**	20689	**45.07%**	23862	**36.64%**
Total CO2 Emission (kg/a)	9657	6217	**35.62%**	3700	**61.69%**	597	**93.82%**
Total Cost (GBP/a)	£1488	£1311	**11.90%**	£836.00	**43.82%**	£338.00	**77.28%**

4D Modelling for End Users Disruption Simulation

To plan the Phase 2 Retrofit Works with Line of Balance it was necessary to define the retrofit work packages, sequence, duration, crew size and batch size. Based on variations in these definitions, three scenarios for retrofit works were developed using the line of balance. Next, the work packages were classified according to the level of disruption caused for end users. Red represents the most disruptive activities, orange is for medium disruptive ones, yellow activities cause low disruptions, while light green represents the work in progress days. The three line of balances were painted according to the work package classification in order to facilitate the visualization of disruption, as demonstrated in Figure 1, and were imported in the 4D BIM model for simulation.

The line of balance provided information to compare the scenarios Table 2, such as: total duration, duration of most disruptive work packages, number of workers, number of work packages in simulation, number of crews, number of tasks, and days of work in progress.

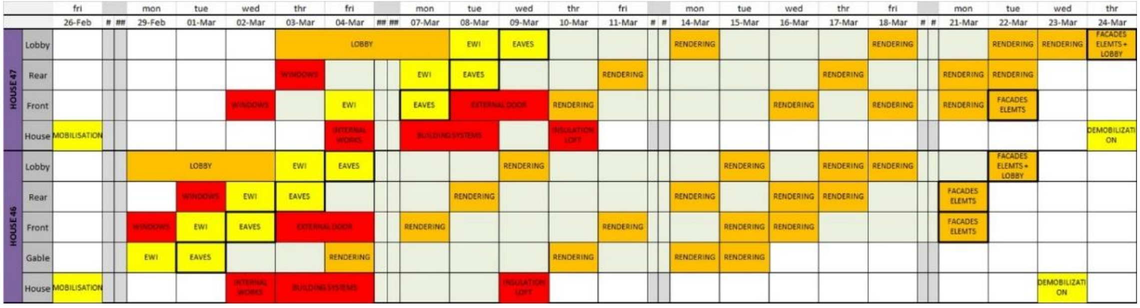

Figure 1. Example of line of balance of scenario 3 with work packages painted according to the end users disruption classification.

Table 2. Results of retrofit works scenarios simulation using line of balance.

	Scenario 1	Scenario 2	Scenario 3
Total duration	20 days	21 days	22 days
Users disruption – internal works (Red): External door, internal works, building systems, and loft insulation	7 days	9 days	7 days
Total of workers	9	7	8
Number of work packages in simulation	12	11	12
Number of crews	6	6	6
Number of tasks	75	60	77
Days of work in progress	47	56	53

Quantities Extraction for Cost

The BIM Model provided data for the costs simulation, such as: 1) Number of windows; 2) Number of external doors; 3) External area to be rendered; 4) External area to be insulated; and, 5) Roof slab area to be insulated. These data were extracted in a MS. Excel sheet in which more data collected from product and services prices were also gathered the presented. Product prices included the heating system, insulation system, render, windows and doors; and service prices included in retrofit works by subcontractor and building services systems installation.

What-If Scenario Matrix

The what-if Matrix is the combination of the three scenarios for energy consumption with the three scenarios for retrofit works to reduce end users disruptions. The cost information is a consequence of these combinations, and for that reason, prices of service and products were calculated separately. As the main aim of the S-IMPLER is to have a cost effective solution for the retrofits, while it should save 60% of energy costs and causes less disruption for the end users, these information were selected to be crossed in the what-if scenario matrix, as shown in the Table 3.

Table 3. What-if matrix crossing information from scenarios simulations in energy savings, disruption days and cost.

		Energy Savings		
		Scenario 1 11.90%	**Scenario 2** 43.82%	**Scenario 3** **77.28%**
Users Disruptions	**Scenario 1** **7 days**	£8,359.54	£ 9,250.00	£ 9,300.00
	Scenario 2 9 days	£8,400.00	£ 9,300.00	£ 9,450.00
	Scenario 3 **7 days**	£8,370.00	£ 9,300.00	£ 9,350.00

4. Case Study Discussion

The location breakdown structure used to plan the master schedule for project phase 2, combined with the work package definition were essential to develop BIM models with the exact amount of elements and data necessary for the simulations. These results are the first step for the development of an integrated planning and controlling process between design and construction.

The what-if matrix developed in the study may be use by the housing association (client) to support decision making. In the matrix the client can visualize the resultant costs of crossing scenarios for energy savings and users disruptions. If the client chooses for the whole life costs of the house, the best solution could be scenario 1 for disruptions and scenario 3 for energy savings.

5. Conclusion

This paper presented how the definition of production batch and the work packages allowed the creation of scenarios for design solutions aiming to improve the energy efficiency of no-fines solid walls housing, and for retrofit works plans using the line of balance and 4D end users disruptions simulations. Moreover, the use of these concepts worked as boundary objects, enabling the connection and development of scenarios for design of retrofit solutions and the planning of retrofit activities. These boundary objects also defined how should the BIM model structure be for the 3D, 4D and 5D simulations.

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