Project management operations and building performance in the construction industry: A multi method approach of applied in a UK public office building

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Abstract

The "performance gap" in the UK building industry is a persistent problem as new building development projects underperform more often than not. Underperformance has to be addressed as the building sector is responsible for a large share of CO_2 emissions in the UK. The "performance gap" arises in part, because building project development involves operations with several stages and actors of different motivations. The outcome of the building project in terms of quality is important and has implications for energy consumption, carbon emissions and occupant well-being. We develop a system dynamics model of building project development operations to explore building quality implications for energy consumption and Indoor Environmental Quality (IEQ). To do this, we couple the system dynamics model to a building physics model and apply them in an empirical case of a recently completed building project. The building performance model is developed and calibrated to reproduce the actual energy performance of the building based on one year of monitoring and post commission data. This is used as a reference point for the system dynamics model that explores additional scenarios of how project operations could deliver better total building performance.

Keywords: project management, operations, simulation, low carbon, system dynamics

1 Introduction

The building sector, which includes residential and commercial structures, accounts for almost 21% of the world's delivered energy consumption in 2015 (EIA, 2017). In the EU, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions[1]. For example, the residential sector in UK accounted for 18% of all CO_2 emissions in 2016 (DBEIS, 2017), and the building sector accounts for more than 45% of UK emissions (Oreszczyn and Lowe, 2010). It is estimated that energy efficiency strategies can reduce a building's energy consumption by 50% to 70% (Zervos *et al.*, 2010). Urgent and ambitious measures are required for the adoption of state-of-the-art performance standards in new and retrofit buildings (IPCC, 2014).

The UK government in 2009 adopted an 80% target of total emissions reduction by 2050. This would require faster emission reduction in the building sector than the current rate (Oreszczyn and Lowe, 2010). Reductions in building energy consumption must also not generate unintended consequences in terms of indoor environmental quality (IEQ) and other performance metrics (Davies and Oreszczyn, 2012; Shrubsole *et al.*, 2014; Shrubsole *et al.*, 2018). Achieving the CO_2 reduction targets by 2050 cannot just depend on combinations of technologies that have dominated over the last three decades or simply a continuation of the current trends (Lowe, 2007).

This poses a considerable challenge as behavioural and factors specific to construction supply chain (CSC) partner interactions in building design, construction and operation project stages influence the long term building quality, energy consumption, and IEQ (Bendoly and Swink, 2007; O'Brien *et al.*, 2009; Alencastro *et al.*, 2018; Gram-Hanssen and Georg, 2018). In this respect, UK

[1] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (accessed 13/2/2018)

government reports have highlighted the need for improvements in the historically fragmented UK building industry (Latham, 1994; Egan, 1998). Project improvements could be achieved through greater integration, and operation coordination at the organisational level between clients and suppliers (Turner and Müller, 2003). Since the publication of the reports, supply chain collaboration has increased in UK construction industry operations practices (Meng, 2013). Despite, some improvement in the energy performance of the existing non-domestic stock, performance gaps remain between the intended and actual performance of new and refurbished buildings[2] (Cohen *et al.*, 2001; De Wilde, 2014).

One reason for this, is the complex and ineffective UK regulatory landscape of incentives for energy efficiency in commercial buildings. This is compounded by the lack of focus by all partners involved in a CSC about what works in practice when it comes to reductions of building energy use and emissions, and what works in practice (Cohen and Bordass, 2015). UK policy should focus more on actual energy use than theoretical estimates, and behavioural drivers for improvement as they are at least as important as financial ones (Cohen and Bordass, 2015) [3]. Given the growing need to achieve low carbon emissions in all industrial sectors by 2050, is it possible to achieve further building performance improvements through collaboration in CSC operations?

The focus on physical project work flows must be complemented with a focus on inter-stage collaboration between CSC project partners to account for UK industry fragmentation. Supply chain collaboration has certain precedents: the goals alignment of project partners and client, the trust between them, information sharing, and antecedents: the delivery of value to the client (Bendoly and Swink, 2007; Hanson *et al.*, 2011; Wong *et al.*, 2012). However, the implications of these antecedents on building performance are not explored in recent project operations management modelling and simulation work (Rahmandad and Hu, 2010; Han *et al.*, 2013; Parvan *et al.*, 2015).

The current paper tries to address this gap, explore and document potential solutions to this problem (Holmstrom *et al.*, 2009). This is done by means of a modelling framework that seeks a sense of theoretical generality while being situationally grounded, methodologically rigorous and practically relevant (Ketokivi and Choi, 2014). The project management part of the framework is sufficiently generic and the building physics part is used to ground the framework in a particular context. The framework aims to explore the effect of CSC collaboration and operations management on operational building performance and IEQ on a case by case basis.

It is the first attempt to bridge buildings and performance gap. The paper follows a multi-methodology approach that combines the technical and social aspects of project management (Mingers and Brocklesby, 1997). Two simulation methods from different domains of expertise are combined in a novel way. System dynamics is used for project management and supply chain collaboration modelling (Sterman, 2000; Lyneis and Ford, 2007; Mingers and White, 2010), and building physics modelling for building performance (Hensen and Lamberts, 2011). System dynamics is often combined with other methods (Howick and Ackerman, 2011; Zolfagharian *et al.*, 2018) and the framework development is geared to tackle a class of problems rather than a single case (Forrester, 1961). System dynamics modelling and simulation has been proposed and explored as a complementary methodological tool to low carbon transition case study research (Papachristos,

[2] Committee on Climate Change (2014). Meeting carbon budgets – 2014 progress report to parliament. London. http://www.theccc.org.uk/publication/meeting-carbon-budgets-2014-progress-report-to-parliament/
[3] Committee on Climate Change (2014). Meeting carbon budgets – 2014 progress report to parliament. London. http://www.theccc.org.uk/publication/meeting-carbon-budgets-2014-progress-report-to-parliament/

2012, 2014a, b; Holtz *et al.*, 2015; Papachristos and Adamides, 2016; Papachristos, 2017; Köhler *et al.*, 2018; Papachristos, 2018).

The framework is applied to a recently completed public office building in UK that followed a design and build procurement approach (Molenaar *et al.*, 1999). Through seven hour-long, semi structured interviews, and a workshop with project stakeholders that focused on the particular project and industry related issues, it is clear that the case has a number of characteristics that make it an appropriate choice for research (Yin, 2003): (i) the building energy performance target set in consultation with the client was Display Energy Certificate A (DEC), placing it in the top 15% in terms of performance in UK, (ii) the project followed a soft landings approach which aims to keep designers and constructors involved in the performance of buildings beyond completion (De Wilde, 2014), (iii) partner alignment and commitment was high as they considered it to be a flagship project in terms of energy and IEQ performance.

The rest of the paper is structured as follows. Section 2 presents an overview of the case building. Section 3 provides the conceptual foundation for the framework. Section 4 present the system dynamics model and discusses how it is coupled to the building performance model. Section 5 presents result of the study for the building and explores the effect of project operations factors. Section 6 discusses limitations and concludes the paper.

2 The Building Case

The case concerns a public office building complex in the UK with 4 storeys, designed for 450 staff. The building is intended for long term use and the client has a vested interest to achieve low operational use costs. The target of the project is to achieve a Display Energy Certificate (DEC) A rating for building performance. The novelty is that the DEC A goals is written into the contract (but no IEQ goal). The project is the first to employ a four-year, post commission, “soft landing” approach[4] during which designers and constructors will try to improve building energy efficiency (De Wilde, 2014). The building is close to but has not yet reached DEC A performance, three years after its commission. Nevertheless, it has won several industry awards as an exemplar for UK public buildings and received wide publicity with a lot of sustainability themed tours around the building attended by industry professionals.

Interviews with seven industry experts that were stakeholders in the research project, were conducted by the same researcher to ensure consistency. They confirmed that such a strong client emphasis on building energy performance is still a niche market segment. Five of them were directly involved in the project and participated in a focused workshop. This provided the research team the opportunity to juxtapose the content of their interviews with the retrospective discussion about aspects of the project. A consensus view formed around some of the points raised in the workshop.

3 The Modelling Framework

The framework adopts a flow view of production in construction supply chains (CSC) (Vrijhoef and Koskela, 2000). The core logic of project management model draws on prior system dynamics work (Ford and Sterman, 1998; Parvan *et al.*, 2015). It involves workflows of project tasks completion, defects[5] that arise in the process, and the decision logic that drives these flows within project and

[4] https://www.bsria.co.uk

[5] Semantics note: tasks and defects are standard terms in the system dynamics project management literature. Defects lead to a deviation in project performance. In the building science literature deviation from project performance arises

between project stages and contribute to building quality. The logic generates project partner collaboration dynamics.

The framework uses *Case Project Input* (Figure 1) on building project characteristics: project timing, resources, stages, and organizational aspects, and the building performance gap i.e. the building areas where known operational building performance deviates from design targets, a widely applied definition in the UK (Cohen *et al.*, 2001). The areas and gap magnitude are established through a *Building Performance Model*. The system dynamics (SD) model is calibrated and uses the *Case Project Input* to endogenously generate *Building Quality Indices* that correspond to the building areas where known operational *Total Building Performance* deviates from its design targets. The underlying assumption in coupling the two models is that building quality can be used as a proxy for building performance (Alencastro *et al.*, 2018). The SD model is then used to explore the operational options that could result in better building quality and thus *Total Building Performance* i.e. energy consumption and IEQ.

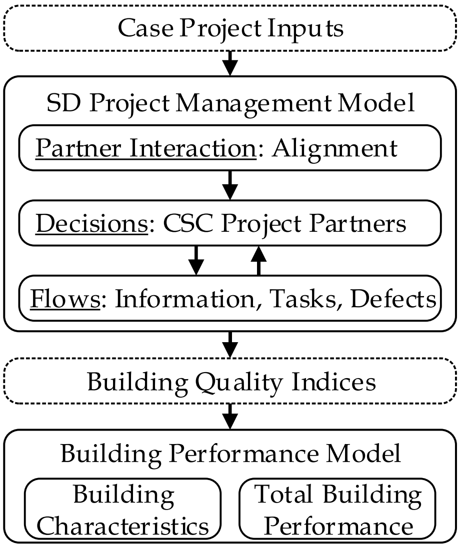

Figure 1 The modelling framework combining project management and building performance

3.1 The Construction Supply Chain

The project management model is based on a simplified construction supply chain (CSC) (Love *et al.*, 2004). Individual organizational actors are aggregated to the organizational level, and CSC organizations are aggregated to the stage level. This aggregation is possible as social entities in hierarchies above the level of individuals can form parts of social mechanisms (Hedström and Swedberg, 1998; Papachristos, 2018). Thus, the CSC consists of design, construction, and operation-client stages each with a respective aggregate actor teams and a related remit of responsibilities (Figure 2).

CSC task flows are based on Ford and Sterman (1998). Tasks are subject to *Quality Testing* at the end of each stage to find defective tasks that lower building quality. A modification on Ford and Sterman (1998) is introduced to increase model realism in line with real construction practice. An additional task flow (solid grey arrows), is used to account for the flow of defective tasks or workarounds to downstream stages due to time pressure, negligence or other limitations (Morrison, 2015; Aljassmi *et al.*, 2016). Project partners choose to do workarounds rather than engage with

from technical defects, and/or deviation from set value parameters. Acknowledging the difference, the terms defects and deviation are used interchangeably in the text.

upstream stages to find a collaborative solution that requires more coordination and time (Aljassmi *et al.*, 2016).

Information exchange is taken into account as it is important for supply chain performance (Lee *et al.*, 1997). Partners exchange information in- and between stages to monitor delivery of work and quality and guard against opportunism (Turner and Müller, 2003). Finally, alignment between actors, facilitates a greater effect as partners share common goals and a shared understanding of how this can be achieved in the project.

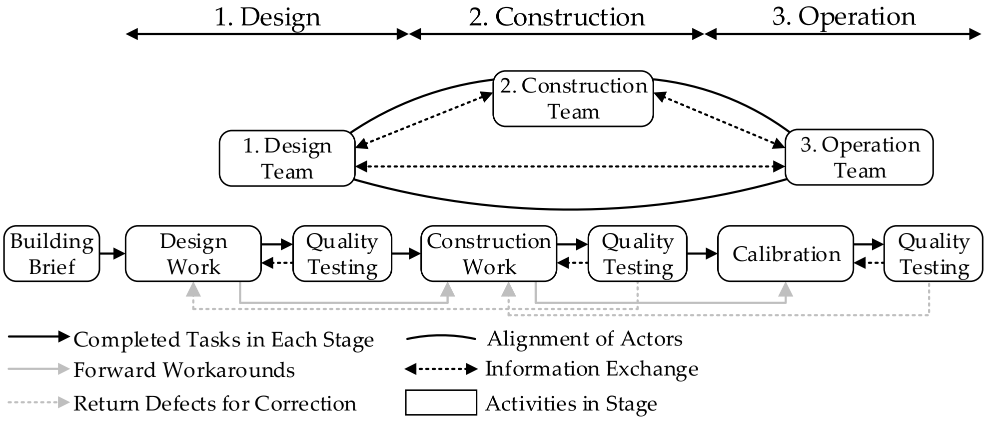

Figure 2 Conceptualization of project stage physical flows between design and construction stages

The conceptual CSC is formalized in an SD model. Figure 3 shows a simplified structure for illustration purposes, of the core task flows between *Design* (1) and *Construction* (2) (the operation stage has the same structure). The flows in grey depend on the particular level of cooperation between CSC partners. In each stage the work and test activities utilize a simple rework cycle formulation.

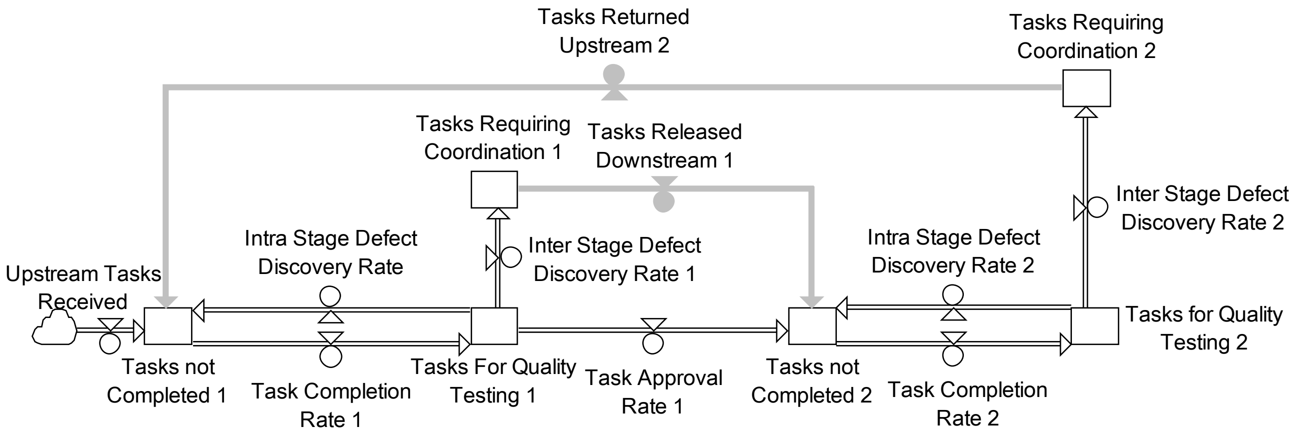

Figure 3 Core stock and flow task structure of two stages of the SD project management model

A co-flow structure (Sterman, 2000) accounts for defects in each stage (Figure 4). Tasks and defects differ and need to be accounted for on a case by case basis as each building is a unique project. An array in the SD model accounts for building areas, with corresponding tasks and related defects. The array forms the interface with the building performance model that enables a detailed analysis of the operational building performance.

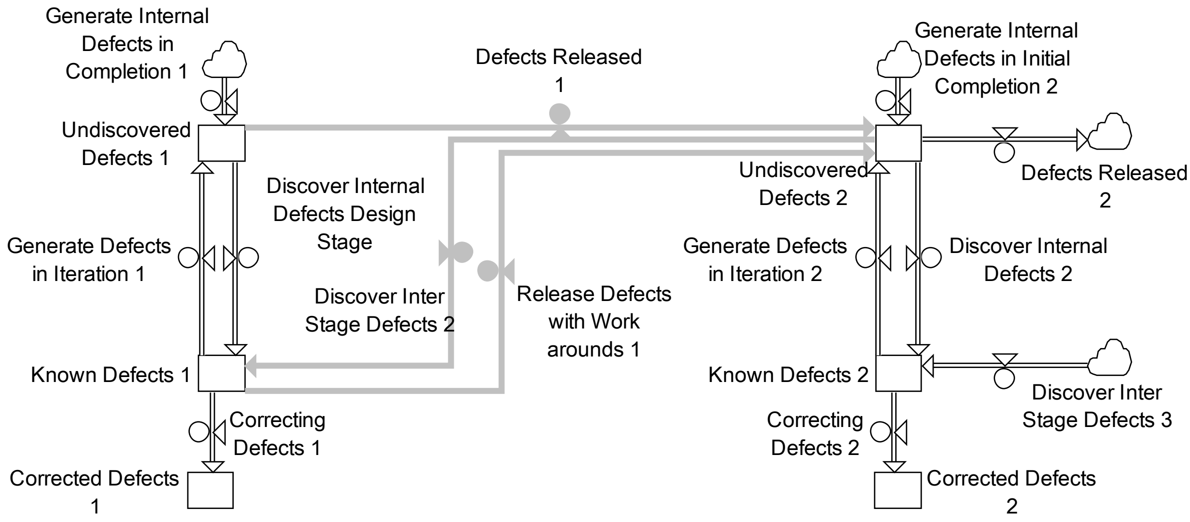

Figure 4 Defect stock and flow structure of two stages of the SD project management model

The task and defect flow structures have a decision and control logic that is driven by partner alignment and information sharing between CSC stages.

4 System Dynamics Model Development

The SD construction project model is developed in Powersim ©[6] and is based on reviewed literature, and Ford and Sterman (1998)[7]. Two of the authors with industry experience provided a sanity check throughout model development.

4.1 Partner Alignment

Organizational alignment research spans the strategic management, supply chain management and project management literatures, and links organizational activities with strategy, and competitive advantage (Powell, 1992; Williams and Samset, 2010; Hanson *et al.*, 2011; Wong *et al.*, 2012; Samset and Volden, 2016; Adner, 2017). It requires clear cause and effect mechanisms, a consensus on strategic goals and actions at the operational level and behaviours towards an operational outcome. Goals provide a rationale for prioritization, resource allocation, and action in project management settings (Brenner, 1994). Goal alignment arises from the logical structure of the project, and the causal link from the basic client needs, defined goals, to the delivery of project results, their outcomes and long-term benefits after the project is terminated.

In the model, intra-stage alignment A_i reflects the level of shared goals in stage i. An initial level of alignment A_i^o, is assumed to exist based on prior collaboration among partners. This level was elicited from interviews and the workshop (see Appendix C). CSC partners must have and sustain a minimum level of alignment and coordination to deliver value to their clients (Gattorna, 2009; Williams and Samset, 2010). Alignment is dynamic as partners make sense of a project, work towards its delivery, and cope with ambiguity, uncertainty and complexity (Weick, 1995). Intra-stage alignment A_i increases with stage duration, which gives partners a chance to interact more. A_i is a stock that accumulates with the rate of aggregate partner engagement E_i per month and faces diminishing returns with stage duration L_i. A_i erodes with partner conflict, or as partner

[6] The model is developed in Studio 10. The complete list of SD equations is in Appendix A. The SD and building physics models are available upon request from the authors.
[7] The detailed working paper version is available from https://dspace.mit.edu/bitstream/handle/1721.1/2644/SWP-3943-36987273.pdf?sequence=1 (accessed 06/02/2018)

participation nears its deadline D_i and other projects become more pressing. Suppressing time subscript t for clarity, A_i is given by:

$$A_i = \int_o^t \left(A_i^o + \frac{E_i}{L_i} - \frac{A_i}{D_i}\right) dt \qquad (1)$$

Inter-stage alignment A_{ij} between stage i and j reflects the level of shared goals across project stages. An initial level of alignment A_{ij}^o is justified as project partners had a history of prior collaboration discussed in the workshop. A high level of A_{ij} implies that CSC project partners are willing to receive and rework defects from downstream stages to improve the overall building quality. An initial level of alignment A_{ij}^o is assumed as project partners had collaborated previously, and they aimed to deliver a high-performance building. It is assumed that intra-stage partner actions in the project are sufficiently visible and considered in their subsequent reciprocal behaviour, so that the motives and constraints of project partners should play a significant role as well (Bendoly and Swink, 2007). $A_{ij}$is assumed to increase with A_i and A_j and is given by:

$$A_{ij} = A_i \times A_j + A_{ij}^o \qquad (2)$$

Alignment is important for performance as a precedent for coordination and information sharing, to eliminate defects, reduce rework and defects, and increase supply chain performance (Briscoe et al., 2004; Kache and Seuring, 2014; Alencastro et al., 2018). High coordination generally results in high quality teamwork and has a positive influence on multi-partner project performance, problem solving, and dispute handling (Hoegl and Gemuenden, 2001; Dietrich *et al.*, 2010; Baiden and Price, 2011; Suprapto *et al.*, 2015).

Information sharing is an important moderator of coordination and shared understanding of project dynamics and project performance (Cohen and Bailey, 1997; Bendoly, 2014). Information is required to complete tasks and reduce uncertainty related to them when they cannot be pre-planned (Galbraith, 1973; Tushman and Nadler, 1978). Information facilitates transparency between CSC partners, responsiveness and lower uncertainty, collaborative planning and risk management (Frohlich and Westbrook, 2002; Barratt, 2004; Soosay *et al.*, 2008; Wong *et al.*, 2012). Project partners share information to coordinate their activities, handle operational and technical issues, and deliver client value (Jingmond and Agren, 2015).

Failure to appreciate the criticality of information flows among stages, and the upstream and downstream effects they can have, can lower communication levels, information quality and increase project rework (Love *et al.*, 2008; Tribelsky and Sacks, 2010; Jingmond and Agren, 2015). The quantity of rework in design and construction stages is inversely proportional to the quality of information stocks (Tribelsky and Sacks, 2011). For example, when building design proceeds with outdated information, it can result in incorrect interpretation and ad hoc amendments by the construction team on-site (Tribelsky and Sacks, 2011; Alencastro *et al.*, 2018).

In the model, inter- and intra-stage information flows are simplified and relate to task work. Alignment influences information sharing once partners engage in project tasks. Communication prior to project start is not modelled explicitly. It is assumed that a maximum stock of information I_i^{max} is required to complete the tasks associated per building area, per stage without defects, and there is no information overflow effects. It is assumed that intra-stage communication flow C_i increases with alignment A_i, and the rate of aggregate partner engagement E_i per month. C_i is given by:

$$C_i = min(E_i \times A_i, I_i^{max} - I_i) \qquad (3)$$

I_i relates to the amount of change in partner understanding, which is extremely difficult to identify and measure (Daft and Macintosh, 1981). I_i is thus defined as the quantity of data that is gathered and interpreted by organization participants i.e. it represents an information stock. Project partners make sense of a project and work towards its delivery as they cope with ambiguity, uncertainty and complexity (Weick, 1995). Inevitably some quantitative information will tend to become out of date as the project progresses i.e. information has a half-life (Samset and Volden, 2016). It is assumed that intra-stage information I_i accumulates with C_i, and erodes inversely proportional to A_i, and stage duration D_i. I_i is given by:

$$I_i = \int_0^t \left(C_i - \frac{C_i}{A_i \times D_i} \right) dt \tag{4}$$

The reciprocal nature of information exchange between stages *i* and *j* suggests a multiplicative relation. It is assumed that inter-stage communication C_{ij} increases with A_{ij}, C_i, and C_j and is given by:

$$C_{ij} = min\left(C_i \times C_j \times A_{ij}, I_{ij}^{max} - I_{ij} \right) \tag{5}$$

The stock of inter-stage information I_{ij} is assumed to erode when project stage ends, and project details are stored away. I_{ij} depends on C_{ij}, stage specific erosion depends on duration D_i and is given by:

$$I_{ij} = \int_0^t \left(C_{ij} - \frac{C_{ij}}{A_{ij} \times D_i} \right) dt \tag{6}$$

4.2 Project Work, Control and Rework

The resources K_i in stage *i* are dynamic and depend on its duration D_i and the total net tasks to be completed T_i. K_i is assumed to represent full time employees, that are reallocated to other projects when T_i declines and falls below K_i. It is given by:

$$K_i = \int_0^t \left(T_i / D_i - (K_i - T_i) \right) dt \tag{7}$$

Project work rate on tasks per building area a, encompasses task completion, quality assurance, and rework, and is subject to K_i. Suppressing a for clarity, the task completion rate R_i per building area for stage *i* is given by:

$$R_i = min(T_i, K_i)/t_i \tag{8}$$

Where t_i, is the time required for task completion. Quality assurance Q_i is influenced by the alignment A_i of state *i* partners to high quality work, and is given by:

$$Q_i = max(0, K_i - R_i) \times A_i \tag{9}$$

Rework in projects is work that has to be repeated and can arise from defects in project execution or from client requirement changes (Love and Edwards, 2004). Defects may arise in any stage, from unrealistic design programmes, organizational culture, quality assurance practices, changes of client needs, and a lack of a common language with which to articulate client requirements in design stage that could lead to misalignment and unnecessary amendments by teams working on-site in subsequent stages (Lopez *et al.*, 2010; De Wilde, 2014; Alencastro *et al.*, 2018). Defects range from few to several hundred, and several kinds of defect classification exist (Alencastro *et al.*, 2018).

Tasks are also assumed to be small enough to be defective or correct but not partially defective (Ford and Sterman, 1998)[8]. The quantity of tasks rework in design and construction stages is inversely proportional to the quality of information stocks, which is assumed to increase with quantity I_{ij} (Tribelsky and Sacks, 2011). The rate of defect generation G_i in stage *i* depends on the rate of task completion R_i, the stage contribution P_i to defects that affect building quality. It is assumed that inter-stage information exchange I_{ij} provides the necessary detail to complete tasks and reduce G_i per building area in stage *I* normalized by the total number of tasks per building area, or scope T_{total} which is assumed to be the same for every building area in every stage. G_i is given by:

$$G_i = R_i \times P_i \times \left(1 - I_{ij}/T_{total}\right) \tag{7}$$

The discovery rate of intra-stage defects F_i in stage *i* depends on quality assurance test Q_i and is subject to resource constraints. F_i depends also on the number of completed tasks to test T_{Fi}, the level of defect testing thoroughness H_i, and the contribution of stage *i* to defects P_i, The defect discovery rate F_i is given by:

$$F_i = min(Q_i, T_{Fi} \times H_i \times P_i) \tag{8}$$

Defects in one stage are detected often in later stages, where they have some knock-on effect, (Sommerville, 2007; Aljassmi and Han, 2013; Alencastro *et al.*, 2018). For example, defects arise frequently in the design stage with mis-communication between client and design team, or between the members of the design team, about building performance targets (De Wilde, 2014). These defects may be discovered by the main contractor in the construction stage through quality assurance. The defects that are discovered in stage *j* and attributed to defects in previous stage *i* depend on the proportion of defects to tasks P_{ij} that flow from stage *i* to *j*, and the proportion k_j of defects possible to rework in stage *j*. F_{ji} is given by:

$$F_{ji} = min\left(T_{Fj}, Q_j - F_j \times P_{ij} \times H_j\right) \times \left(1 - k_j\right) \tag{9}$$

It is assumed that intra- and inter-stage information (eq. 4, 6) can increase quality testing thoroughness H_j, and the probability of defect discovery given the initial scope T_{total} (Tribelsky and Sacks, 2011).

$$H_j = min\left(1, \left(H_{Oj} + \left(I_i \times I_{ij}\right)/T_{total}^2\right)\right) \tag{10}$$

Where H_{Oj} is the initial probability of defect discovery. Nevertheless, some known defects in each stage may not be corrected as most partner resources are reassigned to other projects due to resource and time shortages during a project stage (Love *et al.*, 2002). This reduces project partner capacity to receive tasks for rework, and makes more likely the use of workarounds. This resource shortage effect follows an s-curve[9] and is modelled with a standard logistic s-curve S_j for each stage *j* with value range (0..1) (Sterman, 2000). S_j accounts for resource, costs, time pressure related effects that are not modelled explicitly due to insufficient information, but is also used to simplify the model.

[8] This assumption also becomes more accurate as task size becomes smaller.
[9] Macleamy, P. (2004). Collaboration, Integrated Information, and the Project Lifecycle in Building Design, Construction and Operation. The Construction Users RoundTable. http://www.lcis.com.tw/paper_store/paper_store/CurtCollaboration-20154614516312.pdf (accessed 16/1/2018)

The rate of intra stage defect correction is based on Ford and Sterman (1998)[10] is multiplied by $(1 - S_j)$ to account for resource related stage constrains. The inter-stage return rate of defective tasks R_{ji} from stage j to i depends on k_j, the inter-stage alignment A_{ij} and S_i. R_{ji} is given by:

$$R_{ji} = A_{ij} \times T_{Fij} \times (1 - S_i)/t_{ji} \quad (12)$$

Where t_{ji} is the return delay from stage j to i. As S_i becomes 1 all remaining known defects flow downstream to account for knock on effects on final building quality. The final quality of a building area relative to design targets is assumed to be directly proportional to the ratio of defects over the number of project tasks related to the building area. This ratio provides the quality deviation of building areas from their baseline design operational quality, and is the basis for the interface with the building performance model.

4.3 Interface with the Building Performance Model

The SD project management model interfaces with the building performance model developed in Design Builder simulation software with Energy Plus© as the simulation engine[11]. The SD model produces a quality index output for the building areas with known performance issues (Table 1). This facilitates the interface between the SD and building performance model and the expert knowledge elicitation process about the H_j and P_i variables.

An example of a building area with lower performance than the design target is the heating system efficiency. It is low due to the under sized heating terminals and malfunctioning heat pumps. One element of the task and defect arrays in the SD model is used to trace heating system quality through the project stages. The final quality deviation for the heating system is used as the input in the Design builder model. The Design Builder input parameter is the heating system Coefficient of Performance (COP). It represents the aggregate effect of the heating system issues on the building performance. Table 1 shows the correspondence of SD array elements and Design Builder input.

Table 1 Identified performance issues related to project defects in the case building

SD Array Element	Building Area	Energy Plus Input	Actual Building Defect	Remarks
1	Heating System Efficiency	COP value of heating system	Undersized heating terminals, issues with heat pumps in hot water vessels	COP represents the aggregated system performance
2	Lighting power density	Lighting Load per unit area	Increased lighting load than designed	Direct Input
3	Office equipment power density	Office Equipment Load per unit area	Increased small power load than designed	Direct Input
4	Occupant density	Number of People per unit area	Increased number of people than designed	Direct Input

[10] See eq. 30 in the working paper version of Ford and Sterman (1998), available from: https://dspace.mit.edu/bitstream/handle/1721.1/2644/SWP-3943-36987273.pdf?sequence=1 (accessed16/01/2018)

[11] A simplified, validated version of the building performance model is used to reduce computation time (approximately 24 hours for a single run)

5	Heating Set point	Heating system Set point	Building operating at higher Temperatures than designed	Direct Input (set point maintained during occupied hours)
6	Occupancy hours	Occupancy Schedule hours	Building used for longer hours than designed	Direct Input (hours of weekday occupancy changed).
7	Infiltration	Infiltration Rate	Manually operated vents not shut always/properly	Direct Input
8	Ventilation	Ventilation Control: CO_2 Concentration	Faulty sensors in the building leading to increased CO_2 concentration	Sensor defects can be represented by changes in CO_2 concentration control.

The SD model development for the case building benefitted and used input from two industry experts involved in the research. Both had access, and discussed with multiple project partners (architects, engineers, contractors), they visited the building and conducted four rounds of interviews with the facilities management team in 2016-2017. The experts also developed and calibrated the building physics model of the case building and thus had in-depth knowledge of the performance gap areas in the building. The experts through the analysis they conducted in EnergyPlus ©, pointed to building areas with performance issues and this was used to set number of task and defect arrays in the SD model. Based on their knowledge of the case and their prior experience, they provided expert judgement and input estimates for the SD model on the testing thoroughness of building development quality in each stage, and the contribution of each project stage to the building areas where a performance gap had been identified (Appendix B).

5 Model Simulation

5.1 Model calibration and testing

The SD model uses the following inputs: (i) expert estimate range on the contribution of each project stage P_i to the end quality of the building, (ii) expert estimate range on quality assurance thoroughness H_i at each stage, (iii) work concurrency in, and between stages[12], (iv) difficulty in making task related changes S_i in each project stage, (v) the proportion of upstream defects that are reworkable in downstream stages k_j, (vi) performance gap figures established for the case building through building performance modelling and analysis, and (vii) level of initial alignment. Appendix B provides tables for (i) and (ii), (iii) is given a value of 90% based on expert judgement so that 90% of stage related work has to be completed for downstream stage work to begin, (iv) is set through expert judgement (see Appendix C for details), (v) was set to a value of 0 based on expert judgement on the project, (vi) was provided by building performance analysis (Jain *et al.*, 2017), and (vii) was elicited through project partner interviews.

Model calibration was carried out through numerical optimization to estimate model parameters that minimize SD model output error to performance gap data (Oliva, 2003). The SD model quality index output for building areas with an identified performance gap was less than data based on the building physics model which is calibrated on building monitoring data. It is assumed that knock-on effects have a greater than unit effect, in line with theory (Lyneis and Ford, 2007) and

[12] For concurrence relations see fig. 6-8 in Ford and Sterman (1998).

evidence (Parvan *et al.*, 2015). The knock-on effect of defects N_{ij} from stage i to j per building performance area depends on the sum of undiscovered defects T_{ui} and known defects T_{Fi} normalized against initial design scope T_{total}, and the strength γ of knock on effect. Values for γ are obtained by minimizing simultaneously the performance gap error of model output for each building area (see Appendix C for details). N_{ij} is given by:

$$N_{ij} = (1 + (T_{ui} + T_{Fi})/T_{total})^{\gamma-1} \quad (12)$$

5.2 Simulation Results

To characterize the range of behavior the system produces and to understand the impact of each of its parameters, the model has been extensively analysed. A range of plausible scenarios has been explored to highlight the management and operational trade-offs in such projects. The two independent building performance experts provided input to the model in the form of minimum, maximum, and best estimates for the contribution of each stage to end building quality P_i, and testing thoroughness H_i in each stage. The input space of their best estimates was explored in 729 runs, to produce the output of the possible, average building quality of the nine building areas relative to the maximum value of design building performance of one (Figure 5). The number of tasks for each building area T_{total} is set to 100. Simulation time is five years (see project timeline in Appendix D). All average quality curves illustrate the accumulation of defects that reduce building quality and cause the initial, narrow building quality range to widen. Quality rises as defects are reworked in each stage. Figure 5 broadly reveals that most quality gains or losses are made in construction stage.

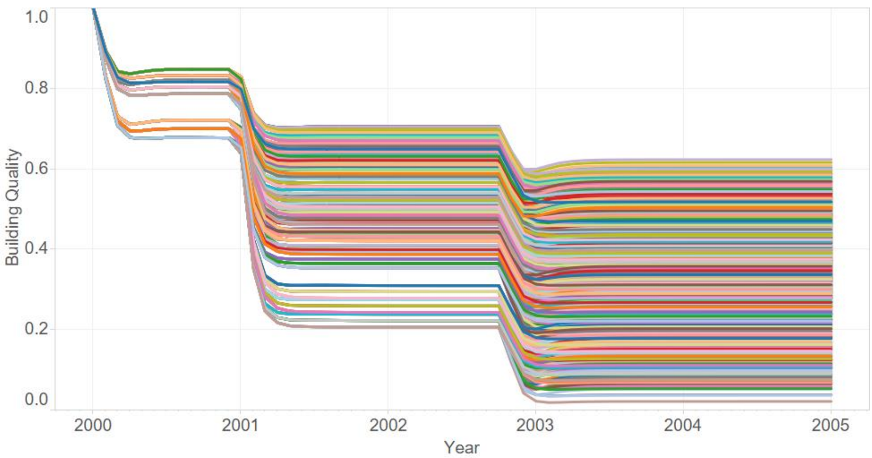

Figure 5 Building quality results using expert best estimates[13]

The breakdown of building performance deviation from design targets in the areas where a performance gap has been observed in reality is shown in Figure 6[14]. On all the defect categories the range of expert input used for produces a min-max range (shaded grey bars) that envelopes the actual real performance (black line). The average value of expert estimates underestimates quality on some building area and overestimates it in others thus there is no clear evidence of bias error.

[13] The actual years of construction have been changed to preserve anonymity.

[14] The ninth area is omitted as performance has been restored to design targets by the end of the 2nd year post commission.

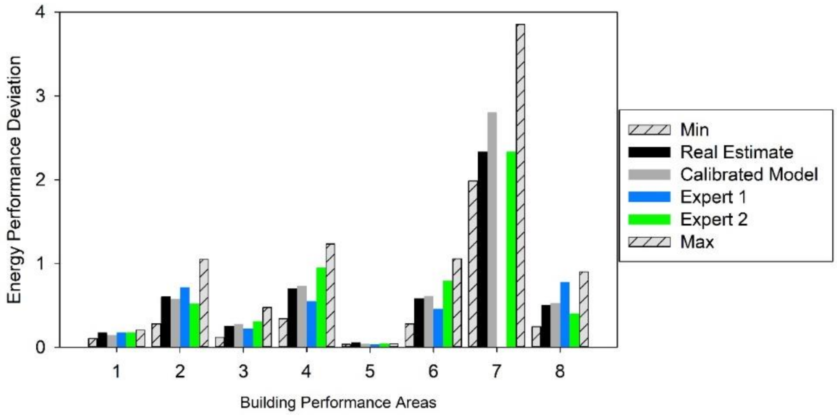

Figure 6 Performance simulation results for building areas with underperformance

The SD output in Figure 6 is the input to the building performance model to generate its corresponding annual energy performance. Figure 7 shows the total energy consumption including electricity and gas (kWh/m^2). Expert 1 results are below min because his input concerns 7 building performance areas (see Appendix B)[15], so the total building performance is better.

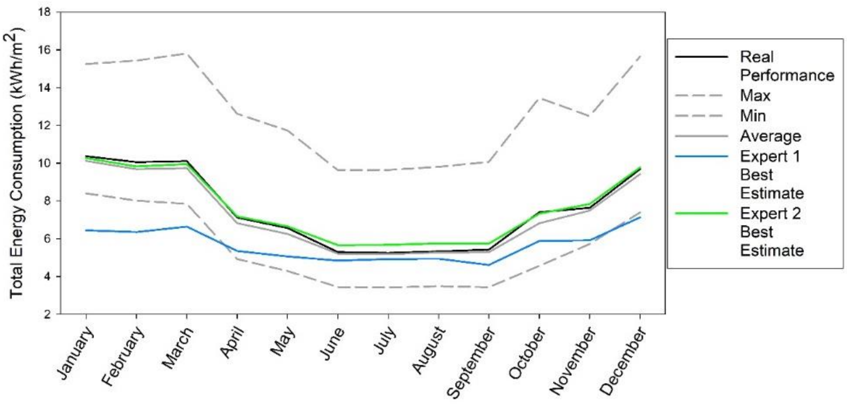

Figure 7 Total, monthly energy consumption from building performance model

5.3 The Effect of Alignment on Performance

Tests for increased, initial CSC alignment in line with UK reports (Latham, 1994; Egan, 1998) show its effect on average building quality (Figure 8, left). Raising intra and inter stage initial alignment from 0 to 2 does result in modest improvement of average building quality 17.67%. The effect of increased inter-stage alignment only is hampered by the level of intra stage alignment that affects intra-stage work quality. However, with resource constraints implemented in both cases, the variation in alignment does not translate into significant building performance figures. The improvement in average building quality is higher when S-curve resource constraints across the three stages are removed and alignment is raised from 0 to 2 (31.05%).

An alignment value of 1 is assumed to be the maximum that a CSC can operate under. A value of 1 in initial alignment with no resource constraints reduces total annual electricity cost by 2.2% and CO_2 emissions by 2.6% compared to the zero-alignment case (Table 2). However, the removal of resource constraints leads also to 4.48% increase in total tasks reworked across all

[15] Expert 1 did not provide estimate for infiltration because he did not have access to the calibrated model for the case building.

stages. This rework needs additional resources and cost, if the project is to be delivered in time. Most of the additional work concerns construction stage tasks and it is done when the project is already in the operation stage. This insight provides some supporting evidence for soft landings approach implemented currently in the UK (De Wilde, 2014). The building performance results suggest that project managers should attend to alignment and resources during project planning since they are critical to success to the project, but they generate also energy use savings and CO_2 emission reductions with more work.

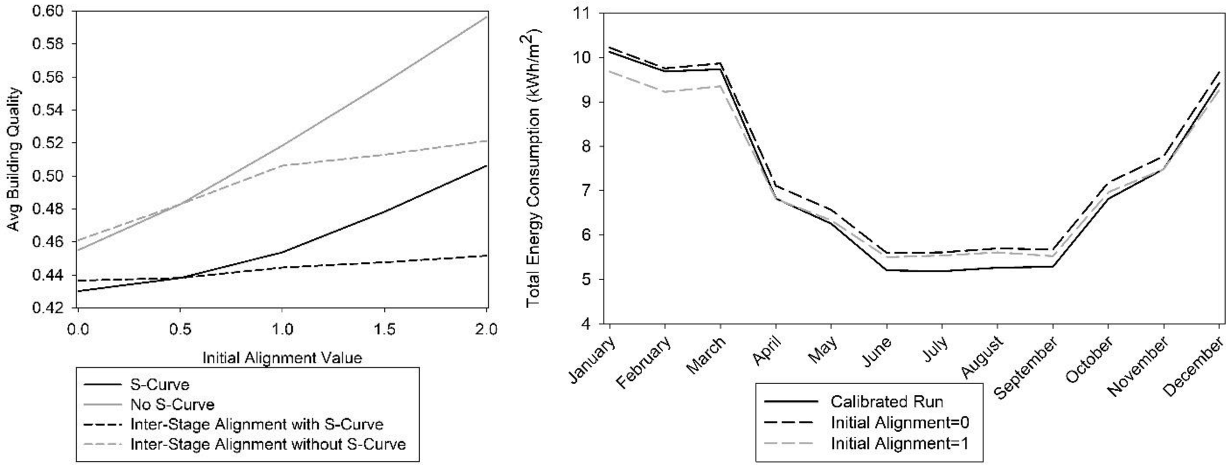

Figure 8 The effect of initial alignment (left) on total energy consumption (right).

Table 2 Annual building performance in scenarios with initial alignment of 1

Annual Performance	Calibrated run	Initial alignment=0	Initial alignment=1
Energy cost (£)	54005.04	57836.18	56555.71
CO_2 emissions (kg)	223808.2	237942.1	231768.3
Work done (tasks)	3066.36	3074.33	3212.07

Figure 8 shows the reinforcing effect of alignment and resource availability, and raises the issue of how to achieve this in practice through appropriately designed contracts that incentivize CSC partners. These results echo the trade-off of the sustainability team leader, who estimated that the time and human resources required for a complete energy modelling study was just not enough, although it was the consensus opinion that it would make a difference in quality. The corresponding results from the building performance model show the performance gains when initial alignment between partners is 1 (Figure 8, right). It results in energy consumption savings and CO_2 emission reduction (Table 2).

5.4 Early Engagement Scenario

Building energy performance is an outcome that arises from complex interactions of building elements and occupant behavior. The inclusion of a high energy performance goal in the building case represents an increase in project complexity relative to the norm for buildings of this type. This raises the need to develop a shared understanding of project targets and communication between project partners (Hong *et al.*, 2004). Clear project targets that are well communicated, understood and accepted improve overall teamwork because project team members engage in goal related functions.

The soft landings approach followed in the case building is designed to keep designers and constructors involved in the performance of buildings beyond completion (De Wilde, 2014). Project partners stay engaged and exchange information, while physical work in each stage may end. A key point for successful team and project development performance is the project team building process around a set of targets such as quality, cost and development time (Hong *et al.*, 2004). An early engagement scenario is simulated where project partners initiate interactions that alignment and communication. Early alignment and information sharing between project partners facilitates clarity on project targets and enables performance.

This scenario was tested by varying information sharing and early engagement between partners in the model. The reference case runs use the actual project timing from the case where partners in design, construction and operation stages engage and start work in month 0, 11.5 and 33 (see Appendix D). It is assumed that project engagement and information sharing is distinct from physical work and can thus start earlier in the project. In this scenario partner engagement begins in month 0 while physical project stage work begins in months 0, 11.5, 33.

The results show that earlier engagement and communication is beneficial to building quality and building performance in building areas (Figure 9). This in support of prior research on the extent of front-end development activities and their influence on project performance where lack of maturity in project definition prior to project execution proved to be responsible for the failure of major projects (Suprapto et al., 2015). The corresponding output from the building simulation model shows a significant reduction in average annual energy consumption of maximum reduction in costs is 28.37% in emissions is 29.25%.

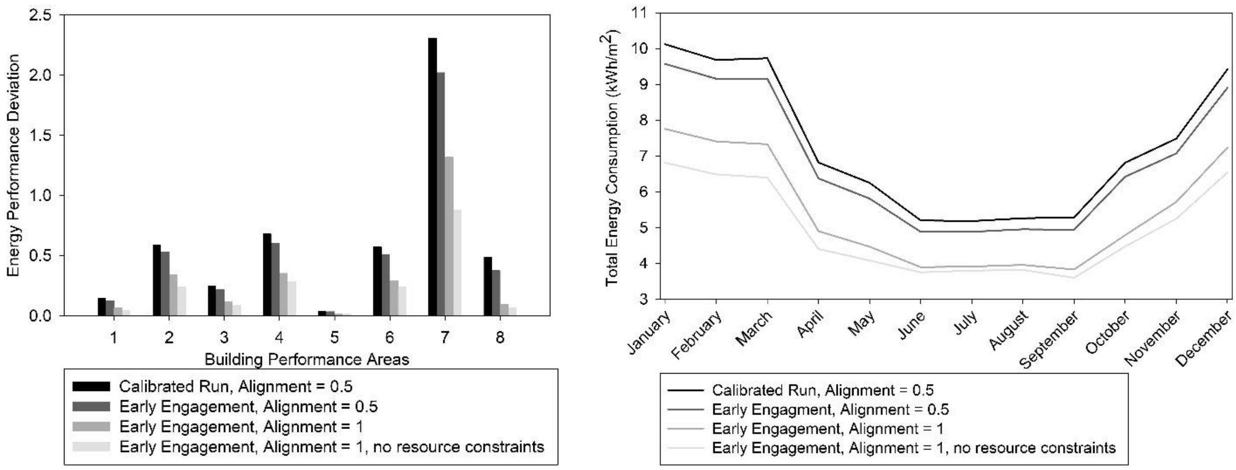

Figure 9 Effect of partner engagement and communication on average building quality (left), and energy performance of building areas.

Table 3 Annual building performance in engagement scenarios with initial alignment of 1

Annual Performance	Calibrated run	Early engagement, Alignment = 0.5	Early engagement, Alignment = 1	Early engagement, Alignment = 1, no resource constraints
Energy cost (£)	54005.04	50959.10	40797.07	38682.01
CO_2 emissions (kg)	223808.2	211053.45	168625.7	158348.2
Work done (tasks)	3066.36	3000.74	2940.62	3139.76

6 Discussion and Conclusions

6.1 Theoretical and Methodological Contribution

The multi-methodology framework developed in this paper contributes to the system dynamics literature on project management. The theoretical contribution of the paper is the integration and operationalization of project partner alignment and information flows in the standard, multi stage project management model (Ford and Sterman, 1998). This facilitates the exploration of collaboration related effects on CSCs that are hampered by fragmentation in the UK and elsewhere. The model structure can facilitate the assessment of project collaboration related effects on building operational performance and CO_2 emissions, a quite topical issue in lieu of climate change, that has been neglected in system dynamics literature. The documentation of the framework and its illustrative application provides a basis to tackle a class of problems rather than a single case (Forrester, 1961). The modelling framework is a first step to explore such effects in more cases to produce generalizable results.

The methodological contribution that enables detailed assessment of operational performance is the novel integration of SD and building physics methodologies that couples the SD project management model to a building physics model. In doing so, the multi-methodology framework seeks simultaneously theoretical generality and situational grounding, while being methodological rigorous and practically relevance to both fields (Ketokivi and Choi, 2014). Data availability on project time and cost will permit a replication of the method in the UK context and the building physics modelling will enable an assessment of the long-term effects of building projects. The intended aim is to produce research that will alter the way industry insiders look at CSC collaboration so that CSC partners then consider seriously mechanisms that permit sufficient, timely and accurate information for CSC governance and building operational performance.

6.2 Practical contributions

The motivation for this paper was the share of the UK building sector to total energy consumption and CO_2 emissions, and its contribution towards the 80% emission reduction target set by the UK government for 2050. This required an explicit focus on the project process that delivers buildings and an in-depth analysis of the implications for operational building performance. Our approach is of particular benefit in building project contracts that include energy performance targets. This is a trend that is picking up pace in the UK and globally (Sorrell, 2007).

The managerial implications of the simulation results are in line with insights from prior work on project performance in terms of cost, time and quality. An early focus on project performance and energy targets is important in terms of operational building energy performance. Encouraging early problem discovery and instituting root cause analysis, energy testing, and capabilities that facilitate quality, can help set the right level of alignment and effectiveness across the CSC. As the set of project uncertainties involved expands to include energy specific targets the project must achieve, project partners and managers should be flexible in updating initial plans when required, and delegate more responsibility to those on the frontlines who often have a more nuanced understanding of the actual tasks, performance and quality.

The challenge in adopting such behaviour in actual operations is that conventional project management performance metrics and tools ignore some of the soft variables and feedback mechanisms that are explored in this model (Browning, 2010). Moreover, the worse-before-better trade-offs involved in upfront quality, organizational capability investments, and cost make it harder to learn and pursue the more flexible learning focused style of project management (Repenning and Sterman, 2002; Williams, 2008). Moreover, building performance improvements cannot depend only on the voluntary learning of organizations in the building industry. Projects are complex entities and learning from complex systems needs a more sophisticated approach than simply writing down lessons (Williams, 2003). Organizations might have procedures for learning lessons from projects but few might adhere to those if they don't perceive immediate benefits in the market, and the transfer of lessons within an organization is one of the major difficulties of learning from projects (Williams, 2008). There is lack of time, management support, and incentive to do so.

6.3 Limitations and Future Work

The study has some data and methodological limitations, and some potential for future development work. The case building was commissioned before it became part of the research project. This limited access to some project partners e.g. the building architect was not interviewed due to new project commitments. It also limited data availability with respect to a number of areas: total project task figures, tasks per building performance area, total resources per stage (due its multi organizational nature), and partner resource prioritization and allocation vis a vis other projects.

Expert judgement was used to calibrate s-curves for each stage and account partially for these limitations. The real building performance is known in detail through in-situ monitoring and building performance modelling, so it is possible to claim that resource related quality effects in each stage have been captured, albeit implicitly in expert estimates on quality and testing thoroughness. Accurate resource availability information would increase the realism of the retrospective analysis and enable a better assessment of the information exchange and collaboration effect on building quality.

One way to overcome such limitations in future framework applications is to follow a building project from its inception to its completion through a process tracing research design (Collier, 2011; Bennett and Checkel, 2014). This would forego the reliance on interviews and post hoc estimates, but most importantly it would increase managerial relevance as it would take on board manager's perspectives explicitly at the outset of research project (Holmstrom *et al.*, 2009).

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References

Adner, R., 2017. Ecosystem as structure: An actionable construct for strategy. Journal of Management 43, 39-58.

Alencastro, J., Fuertes, A., de Wilde, P., 2018. The relationship between quality defects and the thermal performance of buildings. Renewable and Sustainable Energy Reviews 81, 883-894.

Aljassmi, H., Han, S., 2013. Analysis of causes of construction defects using fault trees and risk importance measures. Journal of Construction Engineering and Management 139, 870-880.

Aljassmi, H., Han, S., Davis, S., 2016. Analysis of the complex mechanisms of defect generation in construction projects. Journal of Construction Engineering and Management 142, 04015063.

Baiden, B.K., Price, A.D.F., 2011. The effect of integration on project delivery team effectiveness. International Journal of Project Management 29, 129-136.

Barratt, M., 2004. Understanding the meaning of collaboration in the supply chain. International Journal of Supply Chain Management 9, 30-42.
Bendoly, E., 2014. System dynamics understanding in projects: information sharing, psychological safety, and performance effects. Production and Operations Management 23, 1352-1369.
Bendoly, E., Swink, M., 2007. Moderating effects of information access on project management behavior, performance and perceptions. Journal of Operations Management 25, 604-622.
Bennett, A., Checkel, J.T., 2014. Process Tracing. Cambridge University Press, Cambridge, England.
Briscoe, G.H., Dainty, A.R.J., Milet, S.J., Neal, R.H., 2004. Client led strategies for construction supply chain improvement. Construction Management and Economics 22, 193-201.
Browning, T.R., 2010. On the alignment of the purposes and views of process models in project management. Journal of Operations Management 28, 316-332.
Cohen, R., Bordass, B., 2015. Mandating transparency about building energy performance use. Building Research & Information 43, 534-552.
Cohen, R., Standeven, M., Bordass, B., Leaman, A., 2001. Assessing building performancein use 1: the Probe process. Building Research & Information 29, 85-102.
Cohen, S.G., Bailey, D.E., 1997. What makes teams work: Group effectiveness research from the shopt floor to the executive suite. Journal of Management 23, 239-290.
Collier, D., 2011. Understanding process tracing. Policital Science and Politics 44, 823-830.
Daft, R.L., Macintosh, N.B., 1981. A tentative exploration into the amount and equivocality of information processing in organizational work units. Administrative Science Quarterly 26, 207-224.
Davies, M., Oreszczyn, T., 2012. The unintended consequences of decarbonising the built environment: A UK case study. Energy and Buildings 46, 80-85.
DBEIS, 2017. 2016 UK Greenhouse Gas Emissions, provisional figures. Department for Business, Energy, and Industrial Strategy London, UK.
De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A frameworkd for investigation. Automation in Construction 41, 40-49.
Dietrich, P., Eskerod, P., Dalcher, D., Sandhawalia, B., 2010. The dynamics of collaboration in multipartner projects. Project Management Journal 41, 59-78.
Egan, J., 1998. Rethinking Construction. Department of the Environment, London.
EIA, 2017. International Energy Outlook 2017. U.S. Energy Information Administration.
Ford, D.N., Sterman, J.D., 1998. Dynamic modeling of product development processes. System Dynamics Review 14, 31-68.
Forrester, J.W., 1961. Industrial Dynamics The M.I.T. Press, Cambridge, Massachusetts.
Frohlich, M.T., Westbrook, R., 2002. Arcs of integration: an international study of supply chain strategies. Journal of Operations Management 19, 185-200.
Galbraith, J.R., 1973. Designing Complex Organizations. Addison-Wesley Longman Reading, MA.
Gattorna, J.L., 2009. Dynamic Supply Chain Alignment: A New Business Model for Peak Performance in Enterprise Supply Chains Across All Geographies. Gower Publishing, Farnham, UK.
Gram-Hanssen, K., Georg, S., 2018. Energy performance gaps: promises, people, practices. Building Research & Information 46, 1-9.
Han, S., Love, P., Peña-Mora, F., 2013. A system dynamics model for assessing the impacts of design errors in construction projects. Mathematical and Computer Modelling 57.
Hanson, J.D., Melnyk, S.A., Calantone, R.A., 2011. Defining and measuring alignment in performance management. International Journal of Operations and Production Management 31, 1089-1114.
Hedström, P., Swedberg, R., 1998. Social Mechanisms: An Analytical Approach to Social Theory. Cambridge University Press.
Hensen, J., Lamberts, R. (Eds.), 2011. Building Performance Simulation for Design and Operation. Spoon Press, London.

Hoegl, M., Gemuenden, H.G., 2001. Teamwork quality and the success of innovative projects: a theoretical concept and empirical evidence. Organization Science 12, 435-449.
Holmstrom, J., Ketokivi, M., A-P., H., 2009. Bridging practice and theory: A design science approach. Decision Sciences 40, 65-87.
Holtz, G., Alkemade, F., de Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J., Ruutu, S., 2015. Prospects of modelling societal transitions: Position paper of an emerging community. Environmental Innovation and Societal Transitions 17, 41-58.
Hong, P., Nahm, A.Y., Doll, W.J., 2004. The role of project target clarity in an uncertain project environment. International Journal of Operations and Production Management 24, 1269-1291.
Howick, S., Ackerman, F., 2011. Mixing OR methods in practice: Past, present and future directions. European Journal of Operational Research 215, 503-511.
IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S. , Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Ed.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jain, N., Burman, E., Mumovic, D., Davies, M., Tindale, A., 2017. Improving the energy performance contracting process by managing technical risks and uncertainties using building performance simulation: Lessons from a case study in the UK. The 15th International Conference of International Building Performance Simulation Association, San Fransisco, USA.
Jingmond, M., Agren, R., 2015. Unravelling causes of defects in construction. Construction Innovation 15, 198-218.
Kache, F., Seuring, S., 2014. Linking collaboration and integration to risk and performance in supply chains via a review of literature reviews. International Journal of Supply Chain Management 19, 664-682.
Ketokivi, M., Choi, T., 2014. Renaissance of case research as a scientific method. Journal of Operations Management 32, 232-240.
Köhler, J., De Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G., Chappin, E., 2018. Modelling sustainability transitions: An assessment of approaches and challenges. Journal of Artificial Societies and Social Simulation 21.
Latham, M., 1994. Constructing the Team: Joint review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry. HMSO, London.
Lee, H.L., Padmanabhan, V., Whang, S., 1997. Information distorion in a supply chain: The bullwhip effect. Management Science 43, 546-558.
Lopez, R., Love, P.E.D., Edwards, D.J., Davis, P.R., 2010. Design error classification, causation, and prevention in construction engineering. Journal of Performance of Constructed Facilities 24, 399-408.
Love, P.E.D., Edwards, D.J., 2004. Forensic project management: The underlying causes of rework in construction projects. Civil Engineering and Environmental Systems 21, 207-228.
Love, P.E.D., Edwards, D.J., Irani, Z., 2008. Forensic project management: An exploratory examination of the causal behaviour of design-induced errors. IEEE Transactions in Engineering Management 55, 234-247.
Love, P.E.D., Holt, G.D., Shen, L.Y., Li, H., Irani, Z., 2002. Using system dymamics to better understand change and rework in construction project management systems. International Journal of Project Management 20, 425-436.
Love, P.E.D., Irani, Z., Edwards, D.J., 2004. A seamless supply chain management model for construction. International Journal of Supply Chain Management 9, 43-56.
Lowe, R.J., 2007. Technical options and strategies for decarbonizing UK housing. Building Research & Information 35, 412-425.
Lyneis, J.M., Ford, D.N., 2007. System dynamics applied to project management: a survey, assessment, and directions for future research. System Dynamics Review 23.

Meng, X., 2013. Change in UK construction: Moving toward supply chain collaboration. Journal of Civil Engineering and Management 19, 422-432.
Mingers, J., Brocklesby, J., 1997. Multimethodology: towards a framework for mixing methodologies. Omega 25, 489-509.
Mingers, J., White, L., 2010. A review of the recent contribution of systems thinking to operational research and management science. European Journal of Operational Research 207, 1147-1161.
Molenaar, K., Songer, A.D., Barash, M., 1999. Public-sector design/build evolution and performance. Journal of Management Engineering 15, 54-62.
Morrison, B., 2015. The problem with workrounds is that they work: The persistence of resource shortages. Journal of Operations Management 39-40, 79-91.
O'Brien, W.J., Formoso, C.T., London, K.A., Vrijhoef, R., 2009. Introduction. In: O'Brien, W.J., Fromoso, C.T., Vrijhoef, R., Kerry, L.A. (Eds.), Construction supply chain management handbook. Taylor & Francis Group, London.
Oliva, R., 2003. Model calibration as a testing strategy for system dynamics models. European Journal of Operational Research 151, 552-568.
Oreszczyn, T., Lowe, R., 2010. Challenges for energy and buildings research: objectives, methods and funding mechanisms. Building Research & Information 38, 107-122.
Papachristos, G., 2012. Case study and system dynamics research: Complementarities, pluralism and evolutionary theory development. International Conference of the System Dynamics Society, St Gallen, Switzerland
Papachristos, G., 2014a. Towards multi-system sociotechnical transitions: why simulate. Technology Analysis and Strategic Management 26, 1037-1055.
Papachristos, G., 2014b. Transition inertia due to competition in supply chains with remanufacturing and recycling: A system dynamics model. Environmental Innovation and Societal Transitions 12, 47-65.
Papachristos, G., 2017. Diversity in technology competition. The link between platforms and sociotechnical transitions. Renewable and Sustainable Energy Reviews 73, 291-306.
Papachristos, G., 2018. A mechanism based transition research methodology: Bridging analytical approaches. Futures 98, 57-71.
Papachristos, G., Adamides, E., 2016. A retroductive systems-based methodology for socio-technical transitions research. Technology Forecasting and Social Change 108, 1-14.
Parvan, K., Rahmandad, H., Haghani, A., 2015. Inter-phase feedbacks in construction projects. Journal of Operations Management 39-40.
Powell, T.C., 1992. Organizational alignment as competitive advantage. Strategic Management Journal 13, 119-134.
Rahmandad, H., Hu, K., 2010. Modeling the rework cycle: capturing multiple defects per task. System Dynamics Review 26, 291-315.
Repenning, N.P., Sterman, J.D., 2002. Capability traps and self confirming attribution errors in the dynamics of process improvement. Administrative Science Quarterly 47, 265-295.
Samset, K., Volden, G.H., 2016. Front-end definition of projects: Ten paradoxes and some reflections regarding project management and project governance. International Journal of Project Management 34, 297-313.
Shrubsole, C., Hamilton, I.G., Zimmerman, N., Papachristos, G., Broyd, T., Burman, E., Mumovic, D., Zhu, Y., Lin, B., Davies, M., 2018. Bridging the gap: the need for a system thinking approach in understanding and addressing energy and environmental performance in buildings. Indoor and Built Environment.
Shrubsole, C., Macmillan, A., Davies, M., May, N., 2014. 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock. Indoor and Built Environment 23, 340-352.
Sommerville, J., 2007. Defects and rework in new build: an analysis of the phenomenon and drivers. Structural Survey, 391-407.

Soosay, C.A., Hyland, P.W., Ferrer, M., 2008. Supply chain collaboration: capabilities for continuous innovation. International Journal of Supply Chain Management 13, 160-169.
Sorrell, S., 2007. The economics of energy service contracts. Energy Policy 35, 507-521.
Sterman, J.D., 2000. Business dynamics: Systems thinking and modelling for a complex world. McGraw-Hill, New York, US.
Suprapto, M., Bakker, H.L.M., Mooi, H.G., 2015. Relational factors in owner-contractor collaboration: The mediating role of teamworking. International Journal of Project Management 33, 1347-1363.
Tribelsky, E., Sacks, R., 2010. Measuring information flow in the detaield design of construction projects. Research in Engineering Design 21, 189-206.
Tribelsky, E., Sacks, R., 2011. An empirical study of information flows in multidisciplinary civil engineering design teams using lean measures. Architectural Engineering and Design Management 7, 85-101.
Turner, J.R., Müller, R., 2003. On the nature of the project as a temporary organization. International Journal of Project Management 21, 1-8.
Tushman, M.L., Nadler, D.A., 1978. Information processing as an integrating concept in organizational design. Academy of Management Review 3, 613-624.
Vrijhoef, R., Koskela, L., 2000. The four roles of supply chain management in construction. European Journal of Purchasing & Supply Management 6, 169-178.
Weick, K.E., 1995. Sensemaking in organizations. Sage Publishers, London.
Williams, T., 2003. Learning from projects. Journal of the Operational Research Society 54, 443-451.
Williams, T., 2008. How do organizations learn lessons from projects-and dothey? IEEE Transactions in Engineering Management 55, 248-266.
Williams, T., Samset, K., 2010. Issues in front-end decision making on projects. Project Management Journal 41, 38-49.
Wong, C., Skipworth, H., Godsell, J., Achimugu, N., 2012. Towards a theory of supply chain alignment enablers: a systematic literature review. International Journal of Supply Chain Management 17, 419-437.
Yin, R., 2003. Case Study Research: Design and Methods. Sage, Beverly Hills, CA.
Zervos, A., Lins, C., Muth, J., 2010. Rethinking 2050: A 100% renewable energy vision for the European Union. European Renewable Energy Council.
Zolfagharian, M., Romme, A.G.L., Walrave, B., 2018. Why, when, and how to combine system dynamics with other methods: Towards an evidence-based framework. Journal of Simulation.