Towards the low carbon transition in the construction industry: A multi-method framework of project management operations and total building performance

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Abstract

The building sector is a large contributor to energy consumption and global carbon emissions. In urban environments, most people spend a large amount of their time in buildings, and their indoor environmental conditions can affect occupant health. The total building performance thus spans energy consumption, carbon emissions, and indoor environment. Underperformance in the building sector is frequent, and it is attributed partially to upstream process of construction project management and operations. Current project management approaches focus on quality, cost and time, so a new a framework is required to study this process in terms of total energy performance and explore ways to reduce the total performance gap. A multi-methodology framework is developed in the paper to analyse the effects of building development project process from an operations management perspective, on building energy consumption, carbon emissions, and indoor environmental quality (IEQ). The framework couples a system dynamics project development model to a building physics model. The paper details the steps of the framework along with the data requirements and the way the two models are coupled, so that it can be replicated on a case by case basis.

Introduction

Building energy performance and indoor environmental conditions become increasingly relevant to climate change due to the high building sector emissions and the increasingly urbanized world. The building sector accounts for almost 21% of the world’s delivered energy consumption in 2015 (EIA, 2017), and buildings in the EU account for 40% of energy consumption and 36% of CO_2 emissions[1]. For example, in the UK, the residential sector accounted for 18% of all CO_2 in 2016 (DBEIS, 2017), and the building sector for more than 45% of UK emissions (Oreszczyn and Lowe, 2010). The large impact on climate change implies that urgent and ambitious measures are required for the adoption of state-of-the-art performance standards, in both new and retrofit buildings (IPCC, 2014).

The UK government adopted in 2009 an 80% target of total emissions reduction by 2050. This target implies faster energy consumption and emission reduction in the building sector than the current rate (Oreszczyn and Lowe, 2010). It is estimated that energy efficiency measures can reduce a building’s energy consumption by 50% to 70% (Zervos *et al.*, 2010). However, such measures must avoid unintended consequences on indoor environmental quality (IEQ) conditions and other performance metrics (Davies and Oreszczyn, 2012). The UK target poses a considerable transition challenge for the building industry as behavioural, and project factors specific to construction supply chain (CSC) partner interactions in building design, construction and operation influence directly building quality, energy consumption, and IEQ (Bendoly and Swink, 2007; Alencastro *et al.*, 2018).

UK government reports have highlighted the need for improvements in the historically fragmented UK building industry (Latham, 1994; Egan, 1998). Improvements in building project

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[1] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (accessed 27/3/2018)

performance could be achieved through greater alignment at the organisational and operational level between CSC partners and clients. Since the publication of the reports, supply chain collaboration has increased in UK construction industry operations practices (Meng, 2013). Nevertheless, despite the relatively small improvement in the energy performance of the existing non-domestic stock, evidence suggests that the performance gap remains between the intended and actual performance of new and refurbished buildings[2] (Cohen *et al.*, 2001; De Wilde, 2014).

A fundamental reason for the operational energy performance gap is that it is rarely a project objective. Project performance is usually assessed immediately, often as soon as the delivery stage is over, due to the short-term nature of projects (Turner and Müller, 2003). This implies that project performance is predominantly evaluated in terms of cost, time and quality (Atkinson, 1999). Building project management performance improvements can be facilitated by less industry fragmentation and better CSC relations to deliver high quality buildings. However, these criteria overlook long term, sustainability benefits that become relevant to project management such as energy performance (Huemann and Silvius, 2017; Silvius, 2017)[3]. Their inclusion is necessary for a transition to low carbon sector and climate change mitigation. The criteria will enable CSC partners to focus more on actual project management outcomes, motivated by evidence of which solutions actually work and improve quality and operational energy performance (Cohen and Bordass, 2015).

Few studies address the link between building quality and energy performance (Alencastro *et al.*, 2018), and how project partner relations contribute to construction project performance (Meng, 2012). Effective CSC partner relations have certain precedents: the goal alignment of project partners and client, the trust between them, information sharing, and antecedents: the achievement of firm competitive advantage in the industry and the delivery of value to the client (Bendoly and Swink, 2007; Hanson *et al.*, 2011; Wong *et al.*, 2012). Partner alignment, coordination and information sharing and the effect of building quality on total building performance are important but are not addressed in recent modelling and simulation work on construction project management (Rahmandad and Hu, 2010; Han *et al.*, 2013; Parvan *et al.*, 2015).

To address this issue, a generic multi-methodology systems framework is developed that integrates alignment, coordination, information sharing between CSC partners, final building quality and operational building performance (Shrubsole et al., 2018). The aim is to explore the effect of CSC collaboration and operations management on total operational building performance on a case by case basis. Framework development thus seeks a sense of theoretical generality and methodological rigour, but also of case grounding and practical relevance (Ketokivi and Choi, 2014). Generality is required as many countries attempt to implement policies to improve the environmental performance in building projects and wellbeing of occupants. The objective from a practical point of view is to emphasize the value for money spent across building objectives and increase the likelihood of successful carbon emission reductions. It is hoped that the application of the framework will inform relevant policy and regulations and promote broader project management criteria.

It is the first attempt to bridge two disciplines, project management and building performance in this way. The framework addresses the behavioural and technical aspects of project management (Bendoly and Swink, 2007), and integrates them with case specific building energy and IEQ research. The integration of behavioural and technical aspects requires a multi-methodology

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[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] Special issue on Sustainable Development & Managing Projects in International Journal of Project Management

approach (Mingers and Brocklesby, 1997). Two simulation methodologies are combined in a novel way. System dynamics is used to model project management and collaboration (Sterman, 2000; Lyneis and Ford, 2007), and building physics to model building performance (Hensen and Lamberts, 2011). System dynamics research on project management has produced a class of models (Ford and Sterman, 1998a; Han *et al.*, 2013) that provide the generic basis required for the framework to address the total, operational building performance not just a specific case[4] (Forrester, 1961).

In this respect, the system dynamics model provides the framework with generality and the building physics model provides the grounding to a specific case. In practice, building characteristics diversity will require a dedicated building physics model to assess accurately the performance gap in each case. Thus, the system dynamics (SD) model will have to be calibrated each time to this performance gap. The uniqueness of building projects raises some data availability requirements and calibration issues that are acknowledged where appropriate in framework development (see Appendix A). Nevertheless, the underlying interface logic between the two models is still expected to apply.

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

Simulation Approaches in Building Projects

The application of simulation in building performance, energy, and occupant behaviour research is a fast-growing field (Abourizk *et al.*, 2011). Several supply chain frameworks are used in CSC simulation research (Papadonikolaki and Verbraeck, 2015). A large body of work uses discrete event simulation (DES) e.g. on the effect of resource delays on the project completion time (Akhavian and Behzadan, 2014), construction supplier logistics and the impact of demand fluctuations on lead time and cost efficiency (Vidalakis *et al.*, 2013), the integration of lean and agile principles within the offsite construction concept (Mostafa and Chileshe, 2016), and CO_2 emissions from on-site construction processes (Li *et al.*, 2017). Moreover, simulation approaches are combined in applications like project logistics and environmental impact assessment of buildings (Zhang *et al.*, 2014; Ben-Alon and Sacks, 2017), the integration of building information management (BIM) and DES (Lu and Olofsson, 2014), BIM-based scheduling approach for building projects under resource constraints (Liu *et al.*, 2015). System dynamics has been integrated with: DES (Moradi *et al.*, 2015), fuzzy logic on construction risk allocation (Nasirzadeh *et al.*, 2014), and agent based modelling on feasibility analysis of public investment projects (Jo *et al.*, 2015).

A distinct research stream using SD on project management has also developed and the current framework draws on it (Lyneis and Ford, 2007). An overview of the evolution of the core system dynamics project management model structure is given in Han *et al.* (2013). System dynamics applications include project litigation cases (Cooper, 1980), the impact of client behaviour on project performance (Rodrigues and Williams, 1998), semiconductor chip development project (Ford and Sterman, 1998a), planning and management (Park and Peña-Mora,

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[4] The methodology has been developed along with building industry experts and tested in an exploratory building case, and its core elements are documented in this paper.

2003), theoretical work on tasks with multiple defects (Rahmandad and Hu, 2010), and knock on effects of between design and construction stages on overall project cost (Parvan *et al.*, 2015).

The Modelling Framework

The framework in its current development stage is designed for the retrospective study of project management and total building performance, and the ways it can be improved. It adopts a flow view of production in CSC (Vrijhoef and Koskela, 2000) and uses *Case Project Input* (dotted lines in Figure 1): data on building project time line, resources, stages, and organizational aspects, and the actual building performance gap relative to the project design targets, a widely applied definition in the UK (Cohen *et al.*, 2001). The gap arises in building areas where known operational building performance deviates from design targets. The areas and gap magnitude are established through a *Building Performance Model* (BPM) and analysis with a dedicated simulation software package[5].

The core logic of the *SD Project Management Model* draws on prior system dynamics work (Ford and Sterman, 1998a; Parvan *et al.*, 2015). It involves workflows of project tasks performed and defect flows[6] that arise in the project and lower quality, and the decision logic that drives these flows in, and between, project stages and influences building quality. The logic is assumed to reflect CSC partner collaboration dynamics. The SD model is calibrated to reproduce endogenously the performance gap that the building physics analysis documents in each of the building areas and generate *Building Quality Indices* for them. The underlying assumption in coupling SD and BPM is that building quality is a proxy for building performance (Alencastro *et al.*, 2018). The SD model is used to explore a range of project management options that could improve building quality and thus total building performance i.e. energy consumption and indoor environmental quality.

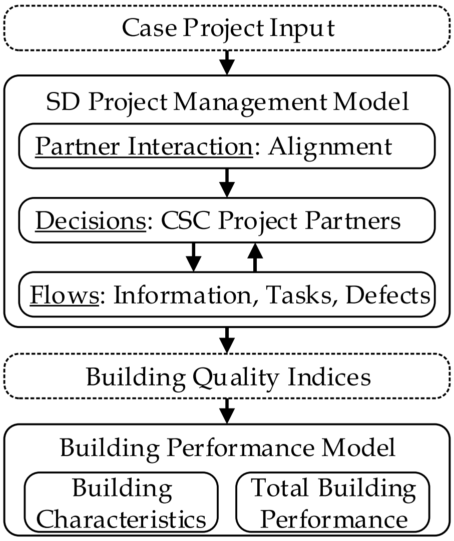

Figure 1 The multi-method modelling framework

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[5] The research project team utilises Design Builder a standard building performance simulation software with Energy Plus© as the simulation engine.

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

The system dynamics model

Building projects involve many CSC partners that operate and interact in, and across project stages, and they are involved and manage the project's physical and information flows. The SD model is based on a simplified CSC (Love *et al.*, 2004) where individual organizational actors are aggregated to the organizational level, and CSC organizations are aggregated to the stage level. Thus, the CSC consists of design, construction, and operation-client stages each with an aggregate partner team and related responsibilities (Figure 2).

Intra and inter-stage CSC task flows are based on Ford and Sterman (1998a). Tasks are subject to *Quality Testing* at each stage to find defects that are reworked in-stage, or returned to upstream stages for rework. Information exchange between project partners improves work quality and defect detection. A modification on Ford and Sterman (1998a) is introduced to increase model validity to real construction practice. An additional task flow (solid grey lines in Figure 2), is used to account for defective tasks, or workarounds, that are released to downstream stages.

Project partners choose to do workarounds rather than engage with upstream stages to find a collaborative solution that requires more coordination and time, due to time pressure, negligence or other limitations (Morrison, 2015; Aljassmi *et al.*, 2016) e.g. construction issues are "patched" onsite without consulting with designers. Workarounds are often problematic because quality assurance, safety, or other standards are usually not followed. Defective tasks can be released to subsequent stages without necessarily being fixed and this can lower the final building quality.

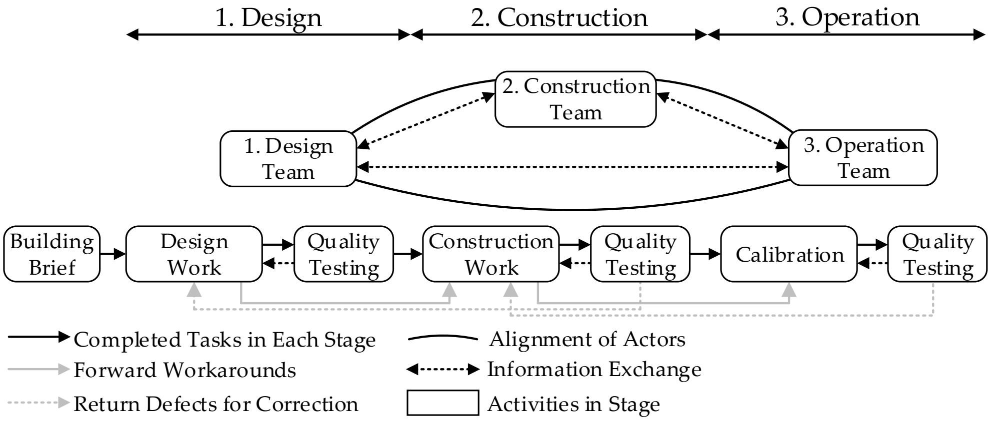

Figure 2 Conceptualization of project stage physical flows between design and construction stages

The conceptual CSC in Figure 2 is formalized in an SD model structure with a co-flow structure to track defect flows (Sterman, 2000). The task and defect flow structures have a decision and control logic. In reality this is complex due to the multi organizational nature of construction projects, different partner goals and levels of coordination and information sharing (Atkinson, 2002; Sommerville, 2007; Davidson, 2009). The requirements on time, cost, quality, and energy performance, and their inter-relations increase project complexity (Baccarini, 1996; Baskhi *et al.*, 2016).

The shared understanding of project scope and the nature of organizational relations are factors of project success (Molenaar and Songer, 1998; Autry and Golicic, 2010; Laan *et al.*, 2011). Goal alignment creates shared interests across partners and motivates them to commit to cooperative action and communication (March and Simon, 1958; Jap and Anderson, 2003). Partners with aligned goals are motivated and commit to cooperative behavior, communication, and mutual support (Jap and Anderson, 2003). Communication of goals and partner responsibilities may increase project performance and reduce the performance gap (De Wilde, 2014).

Nevertheless, project partners do not necessarily share the same view about project success. For example, the use of subcontractors leads to fragmentation in the UK building industry, a low understanding of project dynamics and low performance (Vrijhoef and Koskela, 2000; Briscoe and Dainty, 2005; Bendoly, 2014; Papadonikolaki and Wamelink, 2017). It is necessary to account for alignment and information sharing effects in the SD model.

Model Development

The SD construction project model is developed in Powersim ©[7], and draws on the reviewed literature, and on the detailed, working paper version of Ford and Sterman (1998a)[8]. It is important to note that because projects are unique, model structure may need to be revisited and modified e.g. include additional project stages. The level of SD model aggregation may differ between cases, depending on project specific procurement roots, CSC partners and their roles. The equations in the following sections will need to be revisited and validated on a case by case basis.

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). Alignment at the organizational and interorganizational level motivates actor behaviour towards operational goals. Goals provide a rationale for prioritization and resource allocation policies in project management (Brenner, 1994). Alignment requires a consensus on strategic goals, cause and effect mechanisms (Papachristos, 2018), and actions at the operational level (Hanson *et al.*, 2011).

Alignment applies in single organizations but also extends across partners in a CSC, which is centred around a building project value proposition. Alignment emerges out of client requirements, their interaction with CSC partners and their supplier requirements (Briscoe *et al.*, 2004; Vachon *et al.*, 2009). Requirements about partner behaviour in a project depend partly on whether expectations were met in previous projects (Molenaar *et al.*, 1999; Laan *et al.*, 2011). They constitute a mental model for what to expect and require in a project, that when it is clear and shared it can facilitate information sharing, critical discussion, CSC partner coordination, and problem resolution (Dietrich *et al.*, 2010; Bendoly, 2014).

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, may exist based on potential prior collaboration among partners. The level of A_i^o and the way it develops in each stage and across stages can be elicited through project partner interviews (Ford and Sterman, 1998b). Alignment is dynamic as participants make sense of a project and work towards its delivery as they cope with ambiguity, uncertainty and complexity (Weick, 1995). Intra-stage alignment A_i increases with stage duration, as partners 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 engagement

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[7] The complete list of SD equations is in Appendix B and documentation in Appendix C. The SD and building physics models are available upon request from the authors.

[8] Available from https://dspace.mit.edu/bitstream/handle/1721.1/2644/SWP-3943-36987273.pdf?sequence=1 (accessed 27/03/2018)

approaches 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 e.g. high building quality. An initial level of alignment A_{ij}^o may exist from prior project partner collaboration. It implies that project partners are willing to receive and rework defects from downstream stages to improve building quality. It is assumed that intra-stage partner behaviour is sufficiently visible in the project and considered in subsequent reciprocal partner behaviour (Bendoly and Swink, 2007). $A_{ij}$is assumed to increase with A_i and A_j and is given by:

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

Alignment is important as a precedent for coordination and information sharing, to reduce defects and rework, and increase CSC performance (Briscoe et al., 2004; Kache and Seuring, 2014; Alencastro et al., 2018). Project partner interactions are generally coordinated by the contracts they sign, but information and behavioral aspects influence their daily operations (Love et al., 2002; Ford and Sterman, 2003). Partners exchange information to coordinate their activities, handle operational and technical issues, and deliver client value (Jingmond and Agren, 2015). Information facilitates transparency between CSC partners, high responsiveness and low uncertainty, collaborative planning and risk management (Frohlich and Westbrook, 2002; Barratt, 2004; Soosay *et al.*, 2008; Wong *et al.*, 2012).

Information sharing is an important moderator of alignment, coordination, and shared understanding of project dynamics (Bendoly, 2014). The flow of relevant information can affect partner behaviour in each project stage. Partners with a shared understanding of project dynamics are more likely to appreciate the value of specific information, and supply it to the appropriate partners (Bunderson, 2003). Project defects are reduced by learning through feedback from work processes, and discussion between project partners (Love *et al.*, 2008; Lopez *et al.*, 2010; Bendoly, 2014). Information availability might increase project performance as the shared understanding of the project dynamics coordinates reactions to unanticipated events (Daft and Macintosh, 1981; Bendoly and Swink, 2007; Wong *et al.*, 2012).

Project information flows can be quite complex (Baldwin *et al.*, 1999). To simplify them, it is assumed that alignment influences information sharing once partners engage in project task work, and project information flows as it is made available to members of the project team (Tribelsky and Sacks, 2010, 2011). The initial communication to establish project scope and alignment before its start, is not modelled explicitly. It is assumed that a unit piece of information is required to perform a unit task without any defects, and the delivery of a building area requires 100 tasks in each project stage and an associated maximum of 100 units of information I_i^{max}. 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:

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

Project partners make sense of a project and work towards its delivery as they cope with ambiguity, uncertainty and complexity (Weick, 1995). The amount of change in project understanding relates to the amount of shared information I_i (Daft and Macintosh, 1981). I_i is defined as the quantity of data that is gathered and interpreted by partners i.e. it represents an information stock. 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 erodes inversely proportional to A_i, and stage duration D_i which is determined by project time line (see Appendix A Table 4). 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 a fuzzy min function models information exchange at the limit, when task specific information may be exhausted. C_{ij} is given by:

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

The stock of inter-stage information I_{ij} depends on C_{ij} and it is assumed to erode as a stage approaches its deadline D_i. I_{ij} is given by:

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

Project Control and Rework

Rework in projects is work that has to be done again and can arise from defects in any project stage or from client requirement changes that may affect operational building energy performance (Love and Edwards, 2004; Lopez *et al.*, 2010; De Wilde, 2014). Defects arise out of poor workmanship, lack of quality management systems, client scope changes, lack of supply chain coordination, and insufficient resources and information to execute tasks correctly (Josephson, 2002; Love *et al.*, 2009; Aljassmi and Han, 2013). Defects are often generated in one stage and detected in later stages, where they often have some knock-on effect (Sommerville, 2007; Alencastro *et al.*, 2018). For example, a defect cause is frequently mis-communication in the design stage, about building performance goals between client and design team members (De Wilde, 2014). Design defects are identified usually in construction through internal quality assurance checkpoints, material inspections, and internal and/or external audits.

The number of project defects is used widely as a quality indicator in the building industry. Defects can range from few to several hundred, and several kinds of defect classification exist (Alencastro *et al.*, 2018). Each building project is unique so tasks, defects and building areas with a performance gap need to be accounted for on a case by case basis e.g. heating system, lighting. An array in the SD model accounts for the diversity of tasks, defects and building areas and facilitates the interface with the building performance model that allows a fine-grained building performance analysis in operation.

Rework is inversely proportional to the quality of information stocks which is assumed to increase with quantity I_{ij} (Tribelsky and Sacks, 2011). For example, low information quality and accuracy in construction drawings, can result in incorrect interpretation and unnecessary amendments when the team working on-site proceeds with outdated information (Alencastro *et al.*, 2018). The rate of defect generation G_i per building area a in stage *i* depends on the stage contribution P_i to defects that affect building quality of α, information I_{ij}, the total number of tasks per building area W_{total}, and the rate of work completion R_i. It is assumed that inter-stage information exchange provides the necessary detail to complete tasks and thus reduce defect generation. Intra and inter-stage work concurrence is important for R_i (Ford and Sterman, 1998a), and can be elicited from project partners (see appendix A Figure 2). Suppressing *t* and a for clarity, G_i is given by:

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

The intra-stage defect discovery rate F_j per area a in stage *j* depends on quality assurance Q_j which is subject to resource constraints, the number of tasks to test W_j, the level of testing thoroughness H_j, and the contribution of stage *j* to generating defects P_j. P_i and H_j are elicited from workshops with project partners and building physics experts that have analysed building performance and can trace issues to particular project stages (Tables 1, 2 in Appendix A). Partner resources are assigned to each stage in the model, following Ford and Sterman (1998a).The defect discovery rate F_j is given by:

$$F_j = min\left(Q_j, W_j \cdot H_j \cdot P_j\right) \tag{8}$$

The defects 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:

$$F_{ji} = min\left(W_j, Q_j - F_j \cdot P_{ij} \cdot H_j\right) \cdot k_j \tag{9}$$

k_j is specific to the procurement root used in building development project. It is assumed that information accumulated in a stage and between stages (eq. 4, 6) can improve the testing thoroughness H_i (Tribelsky and Sacks, 2011).

$$H_j = min\left(1, \left(H_{0j} + \left(I_i \cdot I_{ij}\right)/W_{total}^2\right)\right) \tag{10}$$

Where H_{0j} is the initial testing thoroughness level elicited similarly to P_i. F_j increases the defective tasks W_{Fj} found in stage *j*. Some known defects in each stage are not corrected due to resource and time shortages S_j. When the project nears its completion most partner resources are reassigned to other projects as the project has already generated most of the expected revenue. Cost, time and effort constraints for project rework increase as project progresses and they follow an s-curve[9] (Love *et al.*, 2002) that makes more likely the use of workarounds.

The s-curve S_j is modelled with a standard logistic curve for each stage and calibrated on expert input (see Appendix A Figure 1). S_j can account for insufficient information on resource, costs, time pressure related effects but it simplifies the model. The rework rate is based on Ford and Sterman (1998a)[10], and is multiplied by $\left(1 - S_j\right)$ to account for stage constraints. Inter-stage defects are returned to upstream stage *i* subject to k_j and inter-stage alignment A_{ij}. S_i counteracts the effect of A_{ij} on defect return flow R_{ji} from stage *j* to *i*. R_{ji} is given by:

$$R_{ji} = A_{ij} \cdot W_{ij} \cdot (1 - S_i)/T_{ij} \tag{12}$$

Where T_{ji} is the return delay from stage *j* to *i*. When S_i becomes 1 then all remaining 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

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[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)

[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)

number of project tasks for the area. The ratio is the building area quality deviation from its baseline design operational quality, and it is the basis for the interface with the building performance model.

The SD project management model interfaces with the building performance model through the quality index output for the building areas with performance issues. An illustration of such issues drawn from ongoing case research is shown in Table 1[11]. For example, an area with low performance relative to the design stage target is the *heating system efficiency*. The SD model produces a quality deviation figure that is used as the input to the BPM. In this case, the input parameter to the Design Builder is the heating system Coefficient of Performance (COP). The SD model is calibrated through numerical optimization to estimate model parameters that minimize SD model output error to performance gap data documented through building physics analysis (see SD model calibration in Appendix A).

Table 1 Examples of building areas with performance issues drawn from a building case

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

Building Physics Model

The building physics model is developed following a bottom-up approach to represent the physical properties and operating conditions of the building. It is used to evaluate the potential performance in key building areas such as energy use and IEQ. The physical properties of the model include building geometry, fabric characteristics, the mechanical and electrical services and other equipment that is defined as separate components. The model represents also the operating conditions of the building: occupancy pattern, heating and cooling set points and operating hours of the building services. Physics governing equations and engineering first principles are then used to simulate the performance of the building under certain climatic conditions. The simulation runtime is usually a full year to evaluate the building's demand and thermal response across all seasons.

Building performance simulation could be used for three different purposes, at various stages of a building's design and operation. First, in building design, building simulation is used often to evaluate performance and inform designer decisions about building characteristics such as form, shape, external envelope thermal properties, and building services. This can be used to assess the trade-offs between various design choices subject to uncertainty (Ahmad and Culp, 2006). Sensitivity analysis with the model can identify the major determinants of building performance (Lomas and Eppel, 1992; Azar and Menassa, 2012).

Second, building simulation can be used to project operational performance. Deterministic performance projections under given technical specification, operating conditions, and climatic data may be used to define a baseline for operational performance. It is good practice to consider the uncertainty in input space and define a confidence band for these predictions especially where there is a contractual obligation to meet operational targets (MacDonald, 2002; EVO, 2012).

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[11] The methodology has been developed along with building industry experts and tested in an exploratory building case

Third, building simulation can be used to compare the real performance against modelling projections and identify potential defects. It is useful to revisit the design assumptions, adapt the model to the real operating conditions, and define more accurate baselines for performance. Discrepancies between real and projected performance may be indicative of operational issues and could inform building fine-tuning and performance optimisation.

A structured method to gain detailed understanding of building performance is to calibrate the model with monitored data of the building's operational performance based on certain criteria. Uncalibrated modelling is prone to input errors, wrong assumptions and modelling uncertainties (Van Dronkelaar *et al.*, 2016; Imam *et al.*, 2017). Calibration based on overall energy performance without attention to disaggregated energy data (heating, domestic hot water, cooling, lighting, equipment and auxiliary energy) and indoor environmental quality (notably thermal comfort and indoor air quality) may also be misleading.

Calibration requires the systematic collection of operational data for inputs and comparison of the modelling outputs with real performance. Calibration criteria set out the permissible ranges of error between the modelling outputs and real performance such as Normalised Mean Bias Error (NMBS) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE). Energy performance calibration can be used to derive an accurate model of real performance that could then be used for building diagnostics and optimisation (Haberl and Bou-saada, 1998; Raftery *et al.*, 2011; Lam *et al.*, 2014). Table 3 shows the calibration criteria used often for energy performance simulations (ASHRAE, 2014):

Table 2 Calibration criteria used for energy performance simulations

Calibration Method	Calibration Error	
	NMBE	CVRMSE
Hourly method	10%	30%
Monthly method	5%	15%

NMBE and CVRMSE are given in equation 12 and 13:

$$NMBE = \frac{\sum_{i=1}^{n}(yi-\widehat{yi})}{(n-1)\times\bar{y}} \cdot 100 \tag{12}$$

$$CVRMSE = 100 \cdot \left[\sum_{i=1}^{n} \frac{(yi-\hat{y}\,i)^2}{(n-1)}\right]^{1/2} / \bar{y} \tag{13}$$

Where yi is measured hourly or monthly energy use, yi is the hourly or monthly energy use derived from the simulation model, $\bar{y}$ is the average hourly or monthly energy use for the measurement period, and n is the number of data points used (n=8,760 for hourly calibration, n=12 for monthly calibration). Advances in metering strategies and cost-effective, wire-less sensors enable the collection of large amounts of data which can be used to calibrate the model to reproduce the actual building performance with calibration errors significantly lower than the ASHRAE guideline limits (Table 3). For example, Lam *et al.* (2014) report on detailed calibration of a computer model developed for an office building with overall NMBE of 1.27% and CVRMSE of 6.01% while hourly and monthly calibration indices for lighting, equipment and building mechanical services were also within the ASHRAE Guideline 14 limits and modelled air temperatures were consistent with the measurements.

Integration of Building Performance Model and System Dynamics model

The fundamental assumption for coupling the building performance model to the system dynamics model is that the effect of significant defects or workarounds in building design, construction, or operation on energy use and IEQ should also manifest itself in one, or more, input data used in the building simulation model. Then, the calibrated building performance model can reproduce the actual energy use and indoor environmental quality with reasonable accuracy.

Energy performance is used as the key performance metric in the framework (Figure 1), but in principle, IEQ or any attribute of building performance can be used for the same purpose. The process to determine defects and establish the underlying causes of building defects utilising the building performance model of a building:

1. The final as-built building performance model of the building, if it exists, or relevant documentation is reviewed to establish the building design intent with regards to input data and energy performance.
2. A robust energy performance calibration protocol such as ASHRAE Guideline 14 (2014) is selected or defined.
3. Building operation data are captured for at least one full year with installed sensors and the Building Management System (BMS), when the building reaches its steady mode of operation post-occupancy. Supplementary monitoring sensors may be installed to capture required data for calibration.
4. The model is calibrated based on real performance. If the initial design model is not available, a new model is developed in a modelling tool such as DesignBuilder/EnergyPlus.
5. The building operation input data in the calibrated model are compared against the design intents. The output data of the model are also compared against the design intent performance to establish the performance gap. Generally, building operation input data that may lead to underperformance can indicate *defects* in the execution of technical specifications and *deviations* of actual operating conditions from the design assumptions used (e.g. higher heating set point and longer occupancy hours). The technical defects and deviation in operating conditions are identified from the calibrated model. It is critical to understand the *defect* root causes and underlying process and to revisit the assumptions made for operational conditions that led to *deviations*. Deviations are inevitable to some extent given the uncertainties associated with operating conditions at design stage. Nevertheless, deviation bias may indicate significant process issues in a project stage. For example, biased assumptions leading to lower energy consumption in design calculation to ensure certain energy and sustainability ratings are met.
6. An investigation is carried out to understand the causes of identified technical defects and deviations in operating conditions. Generally, there are two types of causes: first order: specific technical issues that directly caused the defect or issues that led to deviations in assumptions, and second order: underlying process issues that led to the first order issues. These causes can be established by: (i) a joint post-occupancy evaluation of the building with the design and construction teams, and users, (ii) an independent building performance evaluation to identify the performance gap causes in-operation and review the design and construction documentations to establish the underlying issues. A hybrid approach is often used in practice where independent evaluators establish the first order causes, and stakeholders are engaged via

semi-structured interviews and workshops to establish a better understanding of the second order causes.

7. The analysis of performance gap causes can be used also to reflect on the building procurement process and estimate the defects and testing probabilities (P_i, H_j) at different stages of the project based on the type of the contract, project official gateways, information available from design, construction, and commissioning documents, and feedback received from stakeholders (Appendix A, Table 1 and 2). This information forms part of the input to the SD model.
8. The analysis of the performance gap provides the necessary input for SD model calibration and provides insights into potential scenario exploration of factors that influence the performance gap.
9. SD model scenarios involve different configurations of CSC partner alignment, project control and rework that result in values for the SD-BPM interface variables.
10. The interface variable values are the input for the BPM that simulates operational performance.

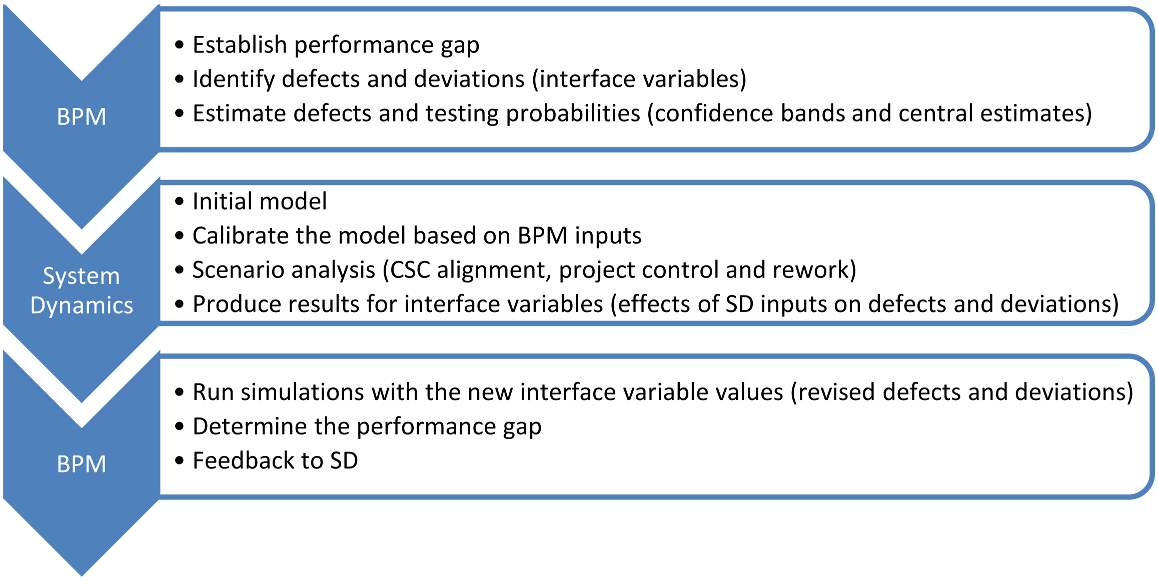

Figure 3. Interface between Building Performance & System Dynamics models and iterative nature of the process

Limitations and future work

The proposed modelling framework has some information requirements and case specific information limitations may impact its successful application. First, limited access to key project stakeholders for interviews may compromise the assessment of project partner alignment and communication flows, how the partners interacted across stages, and whether the SD model needs to be modified for a specific building case. This is an issue whether the framework is applied in a prospective or retrospective way. Second, the number of tasks for each building area in each stage have to be accounted for, or estimated, on a case by case basis. This depends on information availability even if it is in relative terms e.g. heating system might require more tasks than lighting equipment in total over the project duration.

Third, project resource data granularity relies on project partner access which can be challenging due to the multi organizational nature of projects. A concomitant difficulty is resource prioritization and allocation to the project under study vis a vis other projects the partners are involved in over time. Resource availability at the end of a project stage is also important to capture. This information can be captured through interviews but if information availability is low, then s-curves can be calibrated through expert judgement for each stage and account for resource scarcity. Accurate resource availability information will increase the realism of the analysis and enable a better assessment of the information exchange and collaboration effect on building quality. If such information is not available then it is still possible to carry out a more aggregate analysis and claim that resource related quality effects in each stage have been captured, albeit implicitly in expert input on quality and testing thoroughness.

Four potential future developments are envisaged for the framework. First, introduce partially defective tasks in the SD model to increase realism with respect to workarounds. They can be partially defective, but still support the functionality of the systems they are part of and be good enough to go through quality assurance. The quality threshold that can be tolerated in the building and the corresponding defect level for specific building areas is specific to a project.

Second, future SD model development should explicitly account for value engineering and potential conflicts that arise around it, to be able to cope and facilitate exploration of CSC collaborative and adversarial relationships and dynamics on project cost and time performance. The framework in its current development state focuses on building quality, but the effect of CSC partner relationships on time and cost project performance is also important (Meng, 2012).

Third, the assumptions on partner alignment and partner aggregation in CSC stages can be explored more. Disaggregation is an often used technique in system dynamics (Sterman, 2000), and it would require a more detailed a study of intra- and inter-stage interactions, and their precedents. Such a study could be facilitated by following closely a project from its start to establish the frequency and related characteristics of communication. The interview guides used should also be adapted to the needs of the research each time.

Fourth, the modelling framework could be developed so that the construct of project alignment would be unpacked and become more relevant for policy making purposes. Building on the third point, the exploration of alignment effects on building performance could emphasize the importance of project governance (Williams and Samset, 2010; Samset and Volden, 2016). It is a relevant issue in the project management community and pertains to the question of what would be the optimal mix of regulations, economic means and information to improve project governance regimes. An issue to be addressed for the project management community is to shift their perspective beyond the delivery of the project itself and onto the broader issues of the project's utility and effects.

Further work could explore the potential overlap and integration with Building Information Modelling (BIM), a methodology with technological, agential and managerial components (Oraee *et al.*, 2017). This is a fruitful direction for development as a systematic consideration of the managerial aspects of BIM seems to be missing in the literature (He *et al.*, 2017). Organisational aspects of BIM-enabled sustainable design have not been addressed sufficiently in the literature. The biggest challenge is the lack of coordination among people, tools, deliverables, and information requirements. Something that the current framework can be further developed to address. Significant BIM related cost reduction benefits and time savings are reported in the literature, but there could be additional benefits too (Bryde *et al.*, 2013).

The potentially successful adoption of BIM in the industry generates the need to improve management practices and stakeholder relations. For example, in BIM-enabled sustainable building design in early project stages, environmental sustainability considerations are often treated as an add-on to building design, following ad hoc processes for their implementation. As a result, the most common problem to achieve a sustainable building outcome is the absence of the right information at the right time to make critical decisions (Zanni *et al.*, 2017).

Conclusion

The motivation for this study is the large share of the building sector to total CO_2 emissions, and its potential contribution towards emission reduction target set by most developed and developing nations. This requires an approach that facilitates the analysis of the management process involved in new building projects, and the subsequent analysis of the implications for operational building performance. To enable this a modelling framework is developed that couples two methodologies and two disciplines: operations management and system dynamics and building physics and building performance.

The project management SD model in the framework integrates three behavioural operations concepts of project management: partner alignment, coordination and information sharing. This accounts for the social aspects and motivations of project partners to deliver a high-quality building. The SD model is coupled to a building performance model which is calibrated and used to reproduce the operational building performance levels, provide a picture of its CO_2 emissions, and indoor environmental quality, and facilitate a detailed assessment of the areas where a performance gap exists. The SD model uses case specific information and expert-based input to reproduce this performance gap. Subsequently, it can be used to explore project governance interventions that span the alignment, coordination and information sharing among project partners. Simulation results through the interface with the building physics model can provide a detailed picture of project governance effects on operational building performance, energy consumption and CO_2 emissions.

The developed framework is relevant to industry partners in the construction industry as it adopts a supply chain perspective. It can provide the trigger for CSC project partners to think and act strategically to overcome industry fragmentation, through operations management. The proposed framework can be the basis to consider voluntary coordination mechanisms that permit accurate and timely information sharing across the CSC and evaluate their building performance implications. The novelty of the modelling framework lies in its use to project development studies, with a particular focus on the implications of project management on total building performance and CO_2 emissions. The modelling framework is a first step to explore this effect in detail. Future research will see its application to case buildings and the inference of generalizable insights for policy making.

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