Low carbon building performance in the construction industry: A multi-method approach of system dynamics and building performance modelling

Abstract

The construction industry contributes significantly to energy consumption and carbon emissions. Moreover, people spend more time inside buildings, so their health is increasingly influenced by indoor environmental conditions. When considered through these lenses, the concept of total building performance can span energy consumption, the associated CO_2 emissions, and indoor environmental quality (IEQ). At the individual project level, building underperformance with respect to energy and IEQ is frequent, and the ex post performance gap is partially attributed to the construction project management and operations phase of the building lifecycle. This underperformance motivates the research of this paper into the construction process outcomes in terms of energy performance and IEQ, and ways to reduce the performance gap. The paper develops a multi-methodology framework to analyse the effect of building development project process on energy performance and IEQ from an operations management perspective. The framework couples system dynamics modelling of construction project management to building performance modelling. The paper details the way they are coupled, the application steps and data requirements, so that they can be applied on a case by case basis. The aim is to combine operations management to building performance disciplines and deliver insights for industry practitioners and policy makers.

Keywords: project management, low-zero carbon, simulation, building performance, system dynamics

Introduction

Building performance in terms of energy consumption and indoor environmental quality (IEQ) becomes increasingly relevant to, and is affected by, climate change due to the high construction industry emissions and an increasingly urbanized world. The construction industry consumes almost 21% of the world's delivered energy (EIA, 2017:94), and buildings in the EU account for 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2018). The large share of buildings on global emissions and thereby 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).

In 2019 the UK government adopted an 100% target of total emissions reduction by 2050 compared to 1990 levels (Committee on Climate Change, 2019). If this target is to be met, then all industrial sectors, including construction, must make substantial progress and lower their total environmental impact. This implies a transition, a radical shift in construction practices, and knowledge at the project level. Such change departs from incremental improvements and small fixes, and requires much faster, radical shifts to new practices that will reduce energy consumption and emission in the construction industry (Oreszczyn and Lowe, 2010). The UK target poses a considerable transition challenge for the construction industry as behavioural and project factors specific to partner interactions related to building design, construction and operation in a construction supply chain (CSC), influence directly building quality, energy consumption, and IEQ (Bendoly and Swink, 2007; O'Brien *et al.*, 2009; Alencastro *et al.*, 2018; Gram-Hanssen and Georg, 2018). The challenge is compounded as energy efficiency measures can reduce building energy consumption by an estimated 50% to 70% (Zervos *et al.*, 2010:51), but they must avoid unintended consequences on IEQ conditions and other performance metrics (Davies and Oreszczyn, 2012; Shrubsole *et al.*, 2014; Shrubsole *et al*., 2018).

UK government reports have highlighted the need for improvements in the historically fragmented UK construction industry (Latham, 1994:25-29; Egan, 1998:18-31). These reports indicate and recommend that improvements in construction project development can be achieved through greater alignment at the organisational and operational level between CSC partners and construction project clients. Supply chain collaboration has increased in UK construction industry since the publication of the reports (Meng, 2013). This resulted in relatively small improvements in the energy performance of the existing non-domestic stock, but evidence suggests that the performance gap remains between the intended and actual performance in new and refurbished buildings[1] (Cohen *et al.*, 2001; Menezes *et al.*, 2012; De Wilde, 2014). Thus, the challenge at the construction project level persists.

A fundamental reason for the operational energy performance gap is that building energy performance evaluation at design and construction stage is covered by Part L of the Building Regulations in the UK (HM Government, 2013), but operational energy use is rarely a project objective. When building performance is assessed, it is usually done at design stage, at building completion and before handover, due to the short-term and focussed nature of projects (Turner and Müller, 2003). The range of project performance assessment criteria has been extended to include long term sustainability benefits that have become relevant in current project management practice (Huemann and Silvius, 2017; Silvius, 2017)[2]. Their inclusion is necessary to facilitate the low carbon transition of the building industry and climate change mitigation[3]. The criteria will enable CSC partners to focus more on actual project management outcomes, and to improve quality and operational energy performance motivated by evidence of which solutions work (Cohen and Bordass, 2015).

Few studies address the link between project partner collaboration and construction project performance from different perspectives (Meng, 2012), and building quality and operational building performance (Alencastro *et al.*, 2018). This paper is the first attempt to bridge the disciplines of project management and building performance through the development of a multi-

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[1] 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/

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

[3] Building performance includes energy, emissions related to it, IEQ and also other architectural and functional aspects.

methodology framework that links alignment, coordination, and information sharing between CSC partners with project performance, and couples them with final building quality and operational building performance. The paper addresses the behavioural and technical aspects of project management (Bendoly and Swink, 2007), and integrates them with case-oriented building energy and IEQ research in a multi-methodology framework (Mingers and Brocklesby, 1997). Two simulation methodologies are coupled in a novel way. First, system dynamics is used to model project management and CSC collaboration (Sterman, 2000:55; Lyneis and Ford, 2007; Mingers and White, 2010), and second, building physics principles are used to model building performance (Hensen and Lamberts, 2011; De Wilde and Augenbroe, 2015).

The framework is intended for exploration of CSC operations management effects on operational building performance, and its application in a case is documented in Papachristos *et al*. (2018a; 2020). The development of the framework thus seeks a theoretically based generality and methodological rigour, but also practical relevance as it can be applied on a case by case basis (Ketokivi and Choi, 2014). By generality we imply that the application of the framework is not restricted by building type, ventilation strategy, or construction project type. Generality is required as many countries attempt to implement policies to improve building project performance and occupant wellbeing. It is important to note that while the framework is conceptually generic, it has to be adjusted for application to the particular characteristics of a project as each project is unique in many aspects.

The combination of methods is dictated by the framework objective to facilitate the investigation of the effect of project development dynamics on operational building performance. System dynamics (SD) research on project management has produced a class of models (Ford and Sterman, 1998a; Han *et al.*, 2013) that provide a good generic basis for the framework to address project development dynamics. SD work on construction project management in particular is geared towards the investigation of high client value delivery in the construction industry i.e. the delivery of high-quality buildings on time and on budget (Atkinson, 1999). SD work explores project dynamics up to project completion and building delivery, but it does not explore their direct implications for operational building performance (e.g. Ford and Sterman, 1998a). There is a pragmatic difficulty in doing so as the available SD simulation software tools are not suitable for simulation of building operation in detail.

However, the analysis of operational building performance is necessary to assess potential reductions in building energy use and carbon emissions. Current building performance modelling methods and tools are appropriate for this task, but not for the analysis of project management dynamics in the construction supply chain, an issue for which system dynamics modelling and simulation work can contribute a solid foundation (Lyneis and Ford, 2007). Thus, to investigate the influence of project dynamics on operational building performance, it is necessary to couple system dynamics to building performance modelling.

Our framework is particularly relevant for building projects that include energy performance targets, a rising trend in the UK and globally (Sorrell, 2007; Nolden and Sorrell, 2016). The framework can function as a post-project review tool to facilitate learning for project partners, and it can be adapted also as an education and training tool for academics and practitioners. The application of the framework aims to develop lessons and insights to inform relevant policies and regulations, to increase the likelihood of successful carbon emission reductions and better IEQ, and thus to contribute towards the low carbon transition in the construction industry.

It should be noted that the evaluation of building performance is not limited to energy and indoor environmental quality (Papachristos, 2015; Papachristos *et al.*, 2020). The focus of this paper is on energy performance and indoor environmental quality but other aspects of building performance such as financial performance, productivity, health and safety could also be evaluated (Lai and Man, 2017). Adopting the building systems framework first proposed by Markus *et al.* (1972) for building performance evaluations, energy can be viewed as an input to the building system that will affect IEQ as an output of the environmental system. Specifying passive measures that reduce a building’s thermal demand can help improve its energy performance. Advances in thermal comfort theory such as the concept of adaptive thermal comfort (de Dear and Brager, 2002; ASHRAE, 2017) allow further reductions in energy use as a result of wider tolerance bands in system outputs where natural ventilation is used. The optimisation of building performance therefore requires attention to the inputs and outputs of a building's environmental systems.

The rest of the paper is structured as follows. The second section provides a brief overview of building project simulation and outlines the modelling framework. The third and fourth sections outline the framework development, present the system dynamics part of the framework and the data requirements for its application and interface to building performance modelling. The fifth section discusses limitations and future research, and the last section concludes the paper.

Background of Building Project Simulation Approaches

Construction Project Simulation

The application of simulation in the construction sector is a fast-growing field where several supply chain frameworks and paradigms are used in CSC simulation research (Abourizk *et al.*, 2011; Papadonikolaki and Verbraeck, 2015). A large body of work uses discrete event simulation (DES), for example, on the effect of resource delays on construction 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 construction project logistics and environmental impact assessment of buildings (Zhang *et al.*, 2014; Ben-Alon and Sacks, 2017), the integration of building information modelling (BIM) and DES (Lu and Olofsson, 2014), and BIM-based scheduling approach for construction projects under resource constraints (Liu *et al.*, 2015).

System dynamics is used for case-based research (Papachristos, 2012; 2018), project management (Lyneis and Ford, 2007; Mingers and White, 2010, Sterman, 2000; Willliams, 2002), and supply chain collaboration or competition (e.g. Adamides et al., 2012; Papachristos and Adamides, 2014; Papachristos, 2014). 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 of public investment feasibility of construction projects (Jo *et al.*, 2015).

The framework in this paper draws on a distinct literature stream that uses system dynamics (SD) for project management research (Lyneis and Ford, 2007). SD research has produced an appropriate, generic model structure for project management that is geared to tackle a class of problems rather than a single case (Ford and Sterman, 1998a; Forrester, 1961; Han *et al.*, 2013). SD has been applied to project litigation cases (Cooper, 1980), the study of client behaviour impact on project performance (Rodrigues and Williams, 1998), semiconductor chip development projects (Ford and Sterman, 1998a), and planning and management (Park and Peña-Mora, 2003). More recent applications include theoretical work on project tasks with multiple defects (Rahmandad and Hu, 2010), and research on knock on effects between design and construction stages and implications for overall project cost (Parvan *et al.*, 2015). An overview of the evolution of the core SD research and project management structures is given in Lyneis and Ford (2007) and Han *et al.* (2013). These studies focus on client value of project performance in terms of quality, cost, and on time delivery (Atkinson, 1999). They aim to provide insights into the causes of work disruption and project overruns during project development but do not explore the direct implications of CSC on operational building performance and IEQ.

The required project performance improvements to deliver high quality, high performance buildings, can be facilitated by less industry fragmentation and better CSC partner relations (Latham, 1994:76; Egan, 1998:8-9). These have certain precedents: the goal alignment of project partners and client, the trust between them, and information sharing. Antecedents include the achievement of firm competitive advantage in the industry and the delivery of client value (Bendoly and Swink, 2007; Hanson *et al.*, 2011; Wong *et al.*, 2012). The effects of partner alignment, coordination and information exchange, and building quality, on total building performance are arguably important, but have yet to be integrated in recent modelling and simulation work on construction project management (Rahmandad and Hu, 2010; Han *et al*., 2013; Parvan *et al*., 2015) with the exception of Papachristos *et al*. (2020).

In an attempt to address this issue, the focus of the analysis on physical project work must be complemented with a focus on CSC project partner collaboration, industry fragmentation effects, and operational building performance. The typically short-term nature of projects (Turner and Müller, 2003; Geraldi *et al*., 2011), requires a behavioural perspective where project management agents use decision rules with emphasis on CSC integration, and short-term reaction to short term feedback (Cyert and March, 1963; Bendoly and Swink, 2007; Gavetti *et al*., 2012). The behaviour and interactions of CSC partners in design, construction and operation project stages influence also the building quality, its long-term energy consumption, and Indoor Environmental Quality (IEQ) (Alencastro *et al*., 2018; Bendoly and Swink, 2007; Gram-Hanssen and Georg, 2018; O'Brien *et al*., 2009; Shrubsole *et al*., 2019). SD work explores project dynamics up to project completion and building delivery, but it does not explore their direct, operational performance implications (e.g. Ford and Sterman, 1998a). There is a pragmatic difficulty in doing so as the available SD simulation software tools are not suitable for simulation of building operation in detail.

However, this is a necessary addition to the analysis as the behaviour and interactions of CSC partners in design, construction and operation project stages influence also the building quality, long-term energy consumption, and Indoor Environmental Quality (IEQ) (Alencastro *et al*., 2018; Bendoly and Swink, 2007; Gram-Hanssen and Georg, 2018; O'Brien *et al*., 2009; Shrubsole *et al*., 2019). The next section discusses relevant building performance modelling work.

Building Performance Simulation

A building performance model (BPM) represents the building's physical properties and operational conditions, and facilitates the evaluation of potential building performance in key areas such as energy use and IEQ. BPM uses physical governing equations and engineering first principles to link these components and simulate building performance under certain climatic conditions. Simulation is usually carried out for a full year to evaluate building energy demand and thermal response across seasons. A weather file with hourly resolution can be used to represent the climatic conditions of the site for dynamic building performance simulation. This can help identify the climatic design potential and appropriate passive measures that will reduce energy use and carbon emissions of a building at the early design phase.

A BPM can be used at various construction project stages to: (i) evaluate building design performance under various scenarios, identify the major determinants of building performance and inform construction design decisions (Lomas and Eppel, 1992; Azar and Menassa, 2012), (ii) assess the trade-offs between design choices that are subject to uncertainty (Ahmad and Culp, 2006), (iii) generate the operational baseline performance of a proposed final building design under given technical specification, operating conditions, climatic data, and uncertainty especially where there is a contractual obligation to meet operational targets (MacDonald, 2002; EVO, 2012), (iv) reproduce the operational building performance once the building is commissioned and in use.

The operational baseline performance facilitates the identification of underperformance areas through the comparison between the projected and real building operational performance (Norfolk *et al.*, 1994; Petersen and Hviid, 2012; Burman *et al.*, 2014; Jain *et al.*, 2017). However, BPMs do not facilitate analysis of operational building performance in terms of CSC project management processes, so few studies assess the impact of poor-quality project management and defects on the energy performance of buildings (Alencastro *et al*., 2018). This is why system dynamics (SD) is used for case-based research on project management (Lyneis and Ford, 2007; Mingers and White, 2010; Sterman, 2000; Williams, 2002), and building physics modelling for building performance simulation (Hensen and Lamberts, 2011). SD has been combined with Building Performance Modelling (BPM) and simulation only in Papachristos *et al*. (2020), and the rest of this paper documents in detail the framework applied in this study.

[Figure 1 near here]

Framework Development

The framework has been developed using research team expertise in building physics, construction project management, and system dynamics. Framework development benefitted from an exploratory case study of an office building commissioned in 2014 in the UK. The case was selected as high energy performance targets were set at the start of the project to achieve a Display Energy Certificate (DEC) A rating as part of the contract (Papachristos *et al*., 2018a; 2018b; 2020). The case was the first to follow a four-year, Soft Landings approach where project partners try to improve building energy performance (De Wilde, 2014). The case, thus, offered empirical data with which to investigate and quantify the effects of project partner collaboration on operational building performance, and validate framework development.

Detailed knowledge about building performance was developed by two research team members with building physics expertise. They discussed with project architects, engineers, and contractors, visited the building and conducted four rounds of interviews with the facilities management team during 2016–2017. The experts developed in-depth knowledge of performance issues in the building as they developed and calibrated a building physics model on monitored building performance data. The model-based analysis showed that the building is close to reaching DEC A performance after its commission, and pointed to performance issues in nine building areas (Papachristos *et al*., 2020).

The knowledge and prior experience of building physics experts in the research team was the basis to assess the project development process. They provided expert judgement and sanity checks during the development of the SD project management model, and input estimates for the SD model scenario tests. Their input was complemented by system dynamics experts of the research team through hour-long, semi structured interviews with seven industry experts. Five were partners in the building project and participated in a stakeholder workshop that provided the opportunity to juxtapose the content of their interviews with a retrospective discussion of the project management process and develop a shared view about aspects of partner collaboration during project development (Papachristos *et al.*, 2020).

The input of the building stakeholders to the framework highlighted the trade-offs that project partners faced during the construction stages e.g. project engagement, energy testing and resource commitment, which modulated the relation between project management and operational building performance (Papachristos *et al.*, 2020). The case-based knowledge, the analysis of this relation and ways to improve operational building performance served as a bedrock to framework development. Owing to the approach taken, the framework is primarily oriented to retrospective case application to explore the relation between project development and total building performance, and identify ways to improve it.

The Proposed Modelling Framework

The framework is designed for the study of construction project management and building energy and IEQ performance, and the ways they can be improved. It adopts a flow view of production in CSC (Vrijhoef and Koskela, 2000) and uses *Case Project Input* (Figure 1) which has two components: (i) CSC related input, and (ii) building performance gap. The gap is derived from identified building defect areas where monitored operational building performance deviates from the brief and design targets. This is an established and applied definition in the UK especially during the early stages of post-occupancy and when a building has reached its steady mode of operation (Cohen *et al.*, 2001). Longer-term performance will also be affected by factors such as deterioration in thermal performance, building maintenance effects, and future climate change (de Wilde *et al*., 2011). However, addressing the defects that are directly linked to the construction project at the early stages of post-occupancy helps to achieve an energy efficient baseline for long-term performance. A building physics analysis determines the performance gap and validates it through BPM for each of the building performance areas that are relevant to energy and IEQ performance (e.g. energy or various aspects of IEQ such as thermal comfort and indoor air quality).

The core logic of the *SD Project Management Model* part of the framework draws on prior SD work (Ford and Sterman, 1998a; Parvan *et al.*, 2015). It involves project task workflows with the corresponding flows of defects[4] that arise in the project, and the decision making logic of project partners that drives these flows in, and between, project stages and influences building quality. This logic is influenced by CSC partner collaboration dynamics. The SD part is calibrated to the performance gap and uses case related input to explore how construction project management can improve building quality and thus building performance (see sections 4.2-4.6 in Papachristos *et al*. (2020) for an example). The SD part generates *Building Quality Indices* for the case building that are used as input for the building performance model that simulates building operation. The underlying assumption is that building quality is a proxy for building performance (Alencastro *et al.*, 2018). The following sections discuss in detail the 4 framework elements (Figure 1) and its application: (1) the *Case Project Input*, (2) the SD part, (3) its *Building Quality Indices* output, and (4) and the BPM. The uniqueness of building projects raises some data availability requirements and calibration issues that are acknowledged where appropriate in framework development.

[Figure 1 near here]

Case project input: Construction supply chain and building performance modelling

Relevant CSC input data include project management data: the building project time line and delivery dates, partner resources build up, the number and duration of the planned stages and their work scope. The project scope describes the amount of work required to complete each phase of development (Ford and Sterman, 1998a). These input data are also used to validate the SD part for a particular building case. Further required information concerns the initial partner alignment in a stage and between stages, as well as information exchange in and between stages. This qualitative

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[4] Semantics note: tasks and defects are standard terms in the SD 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.

information is elicited from direct engagement with project partners through workshops and/or interviews (Ford and Sterman, 1998b).

BPM is used to assess the actual building performance gap relative to the project design targets. This is done through the comparison of the operational to the projected baseline building performance that facilitates identification of performance gap building areas (Norford *et al.*, 1994; Petersen and Hviid, 2012; Burman *et al.*, 2014; Jain *et al.*, 2017). The BPM represents the physical properties and operational conditions of the building e.g. geometry, thermal characteristics of building fabric, building systems e.g. heating, ventilation and air condition systems (HVAC), and operating conditions as separate components (Figure 2). At the building operation stage, the BPM design stage assumptions are updated and the BPM part of the framework is calibrated with data on real operational conditions: the occupancy pattern and equipment use, heating and cooling set points, climatic conditions, and operating hours of the building services. The systematic collection of operational condition data (Van Dronkelaar *et al.*, 2016), and building modeller education (Imam *et al.*, 2017) can help reduce model input errors and uncertainties.

[Figure 2 near here]

The BPM part of the framework simulates building performance for a full year to evaluate the operational annual building energy use, IEQ, and thermal response across all seasons. The available, monitored, operational data for energy and IEQ can then be used for building diagnostics and optimisation (Haberl and Bou-saada, 1998; Raftery *et al.*, 2011; Lam *et al.*, 2014). Monitored data along with onsite observations and semi structured stakeholder interviews help to identify the building areas with a performance gap and its causes. They can be used as the input to calibrate the BPM part to reproduce accurately the actual building energy use and IEQ.

Advances in monitoring strategies and cost-effective wireless sensors enable the collection of large amounts of data for BPM calibration to the real building performance with errors that are significantly lower than the calibration criteria widely used in the industry such as ASHRAE guideline limits (ASHRAE, 2014). The permissible hourly error range between BPM output and real performance is 10% and 30% respectively for the Normalised Mean Bias Error (NMBE), and the Coefficient of Variation of the Root Mean Square Error (CVRMSE), while the corresponding monthly errors are 5% and 15%. Error is calculated with equation 1 and 2:

$$NMBE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{(n-1) \times \bar{y}} \times 100 \tag{1}$$

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

Where y_i is the monitored hourly or monthly energy use, $\hat{y}_i$ is the hourly or monthly energy use derived from the simulation model, $\bar{y}$ is the average hourly or monthly energy use for the monitoring period, and n is the number of data points used (n=8,760 for hourly calibration, n=12 for monthly calibration). In addition to energy use performance, the BPM model will also be calibrated against key IEQ data such as operative temperatures and carbon dioxide concentration levels (proxy for indoor air quality).

Linking the calibrated BPM to the SD part of the framework rests on the assumption that if the calibrated BPM results are within ASHRAE error limits, then the BPM part can reproduce the actual energy use and IEQ with reasonable accuracy. It should be possible to identify in the input data any statistically significant defect or shortcoming in building design, construction, or operation that compromises energy and IEQ. The development of the SD part is discussed next indicating where and how this information is used.

The proposed system dynamics project management part of the framework

Building projects involve CSC partners that operate and interact in, and across project stages, and they are involved in the project's management of physical and information flows. The SD part is based on a simplified CSC where individual organizational actors are aggregated to the organizational level, and CSC organizations are aggregated to the stage level (Love *et al.*, 2004).

Thus, the CSC consists of design, construction, and operation-client stages (Figure 3, top) each with an aggregate partner team and related responsibilities.

Intra and inter-stage CSC flows of tasks and defects are based on the work of Ford and Sterman (1998a). Tasks are subject to *Quality Testing* at each stage to find defects that might be reworked in-stage, or returned to upstream stages for rework. Information exchange between project partners improves work quality and defect detection. A modification to Ford and Sterman (1998a) is introduced to increase realism to real construction practice. An additional task flow highlighted in solid grey lines in Figure 3, is used to account for workarounds that are released to downstream stages.

Project partners may choose to do workarounds to compensate for errors caused by time pressure or other limitations, rather than engage with upstream stages to find a collaborative solution that requires more coordination and time (Morrison, 2015; Aljassmi *et al.*, 2016). In this way, construction issues are solved or “patched” onsite without consulting with designers. Workarounds are often problematic because quality assurance, or other standards are usually not followed. When they are released to subsequent stages without being fully considered and resolved they can lower the final building quality and performance. The conceptual CSC in Figure 3 is formalized in an SD stock and flow structure with an additional co-flow structure to track defect flows (Sterman, 2000:497-500).

[Figure 3 near here]

The task and defect related flows have a decision and control logic which is quite complex in a real world context, 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 building performance, and their inter-relations increase further project complexity (Baccarini, 1996; Baskhi *et al.*, 2016).

As a result of complexity, project partners may have a different understanding about project scope and the nature of organizational relations which are critical to project success in construction and other industries (Songer and Molenaar, 1997; Molenaar and Songer, 1998; Autry and Golicic, 2010; Laan *et al.*, 2011). The effect of complexity on project performance is exacerbated by CSC fragmentation, for example in the UK building industry, that arises from extensive subcontractor use, a low understanding of project dynamics and low incentives to ensure high levels of building performance (Vrijhoef and Koskela, 2000; Briscoe and Dainty, 2005; Bendoly, 2014; Papadonikolaki and Wamelink, 2017).

The delivery of a high-quality building requires some form of CSC coordination, moderated by partner alignment, to facilitate work inspection/checking, workflow control and defect rework. Goal alignment creates shared interests across partners and motivates them to commit to cooperative behaviour, communication and mutual support (March and Simon, 1958; Jap and Anderson, 2003). The communication of goals, partner responsibilities and exchange of other project related information may increase project performance and building quality, and reduce the performance gap (De Wilde, 2014). Thus, it is necessary to account for alignment and information exchange effects in the SD model (see Papachristos *et al*. (2020) for an example).

System Dynamics Development

The development of the SD construction project structure draws on the reviewed literature, and on the detailed, working paper version of Ford and Sterman (1998a)[5]. It is important to note that a dedicated BPM will be required to assess accurately the performance gap in each building case because building projects are unique. The SD stock and flow structure and assumptions may also need to be revisited as the appropriate aggregation level of the SD part may differ between cases, depending on project specific procurement routes, CSC partners and their roles, and data

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

availability. Thus, the generic SD structure developed here cannot be considered as the final version of a fully-fledged model. The SD structure will have to be revisited for application to a specific case and it will have to be calibrated to the performance gap of the case as illustrated in Papachristos *et al*. (2020). The underlying interface logic between the two models is still expected to apply, and the core project management structure in the SD part should be valid owing to the numerous domains it has been successfully applied to (Lyneis and Ford, 2007).

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). Alignment is the extent to which there is mutual agreement among organizations regarding their positions-roles and resultant flows of work in a collective endeavour such as a project. Different organizations may have different end goals in mind, so project participation is conceptually distinct from partner alignment (Adner, 2017). Alignment motivates partner behaviour towards operational goals that provide a rationale for prioritization and resource allocation in project management. Alignment requires a consensus on strategic goals, cause and effect mechanisms, and actions at the operational level (Hanson *et al.*, 2011).

Alignment applies to single organizations but also extends across CSC partners centred around a construction project value proposition. Alignment emerges out of client building requirements, their interaction with CSC partners and their supplier requirements, the causal link to the delivery of project results and the long-term benefits after the project is terminated (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). The perception of prior partner expectations for a new project constitutes a mental model, 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 partner goals in stage *i*. Alignment values range from zero to one, where zero represents a state of CSC fragmentation where project partners just participate and do the minimum necessary to deliver the project. A value of one represents a state of complete alignment where project partners operate as a single organization from project start to finish, they establish or share the same organizational routines and procedures and as such there is a common perception of problems that arise, related knowledge, and ways to address them.

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 partners 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 *inter alia* increases with stage duration that allows more partner interaction. A_i is a stock that accumulates with the overlap of stage partner activities that facilitate engagement E_i, but faces diminishing returns with stage duration L_i. A_i is also considered to erode as partner engagement approaches planned stage duration D_i and other projects become more pressing (eq. 3), or with partner conflict. Suppressing time subscript *t* for clarity, A_i is given by:

$$A_i = \int_o^t \left(A_i^o + \frac{E_i}{L_i} - \frac{A_i}{D_i}\right) dt \tag{3}$$

A_i: intra-stage alignment (unitless)

E_i: partner overlap of activities (unitless)

L_i: stage duration (months)

D_i: stage duration (months)

Inter-stage alignment A_{ij} between stage *i* and *j* reflects the level of shared goals across project stages e.g. the joint pursuit of 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), thus A_{ij} is assumed to increase with A_i and A_j and is given by:

$$A_{ij} = A_i \cdot A_j + A_{ij}^o \tag{4}$$

A_{ij}: Inter-stage alignment between stage *i* and *j* (unitless)

A_{ij}^o: Initial level of alignment (unitless)

Alignment is an important precedent for coordination and information exchange, 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 behavioural aspects influence their daily operations (Love et al., 2002; Ford and Sterman, 2003). Partners exchange information to coordinate their activities, understand project dynamics, handle operational and technical issues, and deliver client value (Bendoly, 2014; 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).

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 in a timely manner to the appropriate partners (Bunderson, 2003). Information availability might increase project performance as the shared understanding of the project dynamics coordinates partner responses to unanticipated events (Daft and Macintosh, 1981; Bendoly and Swink, 2007; Wong *et al.*, 2012). 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).

Project information flows can be quite complex (Baldwin *et al.*, 1999). To simplify them, it is assumed that alignment influences information exchange once partners engage in project task work, and the flow of project information as it is made available to them (Tribelsky and Sacks, 2010; 2011). The initial partner communication to establish the project scope before its start, is not modelled explicitly. To operationalise the model, 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 further assumed that intra-stage communication flow C_i increases with alignment A_i, and E_i. Suppressing t, C_i is given by:

$$C_i = min(E_i \cdot A_i, I_i^{max} - I_i) \tag{5}$$

C_i: intra-stage communication flow (information units per month)

I_i^{max}: maximum information per stage i (information units)

I_i: information per stage i (information units)

E_i: partner overlap of activities (unitless)

A_i: intra-stage alignment (unitless)

The amount of change in project understanding relates to the amount of shared information I_i in stage i (Daft and Macintosh, 1981). I_i is defined as the stock of information that is gathered and interpreted by stage partners. Some quantitative information will tend inevitably to become out of date as the project progresses i.e. information has a relatively short 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. Suppressing t, I_i is given by:

$$I_i = \int_0^t \left(C_i - \frac{I_i}{A_i \times D_i} \right) dt \tag{6}$$

I_i: information per stage i (information units)

C_i: intra-stage communication flow (information units per month)

D_i: stage i duration (months)

A_i: intra-stage alignment (unitless)

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. Suppressing *t*, C_{ij} is given by:

$$C_{ij} = min\left(C_i \cdot C_j \cdot A_{ij}, I_{ij}^{max} - I_{ij}\right) \tag{7}$$

C_{ij} : inter-stage communication between stages *i*, *j* (information units per month)

A_{ij}: Inter-stage alignment between stage *i* and *j* (unitless)

I_{ij}: information exchanged between stages *i*, *j* (information units)

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. Suppressing *t*, I_{ij} is given by:

$$I_{ij} = \int_0^t \left(C_{ij} - \frac{I_{ij}}{A_{ij} \times D_i}\right) dt \tag{8}$$

Project control and rework

Rework in projects is work that has to be repeated and can arise from defects in project execution or from client requirement changes that may affect operational building 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). For example, a frequent defect cause in the design stage is mis-communication about building performance goals between client and design team members (De Wilde, 2014). 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). Design defects are usually identified in construction through internal quality assurance checkpoints, material inspections, and internal and/or external audits.

The number of project defects is widely used as a quality indicator in the building industry. Defects can range from few to thousands, and several defect classifications exist (Alencastro *et al.*, 2018). Each building project is unique so tasks, defects and building areas with a performance gap need to be identified on a case by case basis e.g. heating system, lighting, acoustics, IEQ. An array in the SD part accounts for tasks and defects that correspond to building areas, and facilitates the interface with the BPM that allows a fine-grained building performance analysis in operation (see Table 1 in Papachristos *et al*. (2020) for an example).

Rework is inversely proportional to the quality of information stocks which is assumed to increase with 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 per area α that affect its building quality, the information I_{ij}, the total number of tasks per building area W_{total}, and the rate of work completion R_i. P_i is a two-dimensional, arrayed input (stages x building areas) to the framework with values that range from zero to 100%. It allows the representation of interdependent defects across project stages and expert knowledge is required to provide realistic range estimates, as P_i will vary depending on the nature of the building and the project development route (see Papachristos *et al*. (2020) for an example).

Tasks are assumed to be small enough to be defective or correct but not partially defective (Ford and Sterman, 1998a:37)[6]. 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, and can be elicited from project partners following Ford and Sterman (1998a). Suppressing t and a for clarity, G_i is given by:

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[6] This assumption also becomes more accurate as task size becomes smaller.

$$G_i = R_i \cdot P_i \cdot \left(1 - I_{ij}/W_{total}\right) \quad (9)$$

G_i: rate of defect generation per area α in stage i (tasks per month)

W_{total}: total number of tasks per building area (tasks)

P_i: stage contribution to defects that affect building quality of area α (unitless)

R_i: rate of work completion (tasks per month)

I_{ij}: information exchanged between stages i, j (information units)

The intra-stage defect discovery rate F_j per area a in stage j depends on the number of completed tasks to test W_j, the level of testing thoroughness H_j, P_j and quality assurance Q_j which is subject to resource constraints. Partner resource build up in each project stage, follows Ford and Sterman (1998a)[7]. H_j is a two-dimensional, arrayed input (stages x building areas) to the framework with values range from zero to 100%, just like P_j. H_j will vary depending on the nature of the building and the project development route, so it is elicited from workshops with project partners and building physics experts that have analysed building performance and can trace issues to particular project stages (see Papachristos et al. (2020) for an example). For example, if a building area in the design stage has an impact on more than one area in the construction or operation stage, it is possible to account for such effects with a two-dimensional array in the input for the SD part. Suppressing t and a for clarity, F_j is given by:

$$F_j = min\left(Q_j, W_j \cdot H_j \cdot P_j\right) \quad (10)$$

F_j: intra-stage defect discovery rate per area a in stage j (tasks per month)

Q_j: quality assurance (tasks per month)

W_j: the number of tasks to test (tasks per month)

H_j: the level of testing thoroughness per area α in stage i (unitless)

P_j : the contribution of stage j to generating defects per area α

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[7] See working paper version pages 11-22

The defects discovered in building area α in stage *j* that are attributed to defects in upstream stage *i* depend on the proportion P_{ij} of defects to tasks that flow from stage *i* to *j*, and the proportion k_j of defects possible to rework in stage *j*. Suppressing *t* and *α*, F_{ji} is given by:

$$F_{ji} = min\left(W_j, Q_j - F_j \cdot P_{ij} \cdot H_j\right) \cdot \left(1 - k_j\right) \tag{11}$$

P_{ij}: the proportion of defects to tasks that flow from stage *i* to *j*

k_j: the proportion of defects that is possible to rework in stage *j*

k_j is specific to the procurement root used in a building development project and requires input from building experts to estimate its value. It is assumed that information I_i and I_{ij} can improve the quality testing thoroughness H_j in stage *j* (Tribelsky and Sacks, 2011:96-97). Suppressing *t* and *α*, H_j is given by:

$$H_j = min\left(1, \left(H_{Oj} + \left(I_i \cdot I_{ij}\right)/W_{total}^2\right)\right) \tag{12}$$

H_j: quality testing thoroughness in stage *j* (unitless)

H_{Oj}: the initial testing thoroughness level per area α in stage *j* (unitless)

H_{Oj} is elicited similarly to P_i. F_j increases the stock of defective tasks W_{Fj} found in stage *j*. Some known defects in each stage will not be corrected due to resource and time shortages. When a project stage nears its completion most partner resources are reassigned to other projects as the project has already generated most of the expected revenue. The use of workarounds rather than project rework is more likely as each project stage approaches completion, due to cost, time and resource constraints that follow an s-curve (Macleamy, 2004).

The s-curve S_j is modelled with a standard logistic curve for each stage and calibrated for each stage based on expert input. S_j can account for resource, costs, and time pressure related constraints when there is insufficient project information. To account for stage constraints, the defect rework rate is based on Ford and Sterman (1998a)[8], and is multiplied by $\left(1 - S_j\right)$. The inter-stage defect return rate R_{ji} from stage j to i is subject to k_j, inter-stage alignment A_{ij}, and S_j. Suppressing t and α, R_{ji} is given by:

$$R_{ji} = A_{ij} \cdot W_{Fj} \cdot \left(1 - S_j\right)/t_{ij} \tag{13}$$

R_{ji}: inter-stage defect return rate per area α from stage j to i (tasks per month)

t_{ji} : defect return delay from stage j to i (months)

S_j : level of resource, costs, and time pressure limitations (unitless)

W_{Fj}: the stock of defective tasks per area α found in stage j (tasks)

When S_j 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 residual defects over the number of project tasks completed for the area in the finished building. The ratio is the quality index deviation of a building area from its baseline design operational quality, and it is the basis for the interface with the building performance model.

SD Interface with BPM

The SD part of the framework generates Quality Index Deviation values for the building defect areas that exhibit performance deviations and can lead to performance gap. A value of zero for a particular building area indicates no deviation from design intent and there is no upper limit for the indices. The building areas are used to interface with the BPM and they are categorised under defect categories as per CIBSE AM11 (see Table 1 in Papachristos *et al*. (2020) for a case-based example of building areas). Each defect category has associated building defect areas that can be modelled in any building simulation software[9]. For example, building geometry and zoning include total areas

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[8] 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)

[9] The list of building defect areas under each defect category is based on EnergyPlus software

and volumes, conditioned areas, window to wall ratio, and solar shading. Construction characteristics and material properties include wall U-value, window U-value, window G-value, roof U-value, floor U-value, and thermal mass. Internal heat gains include occupant density, lighting load (max), lighting control, equipment load (max), and equipment control. Ventilation and air infiltration include mechanical ventilation systems (maximum/minimum ventilation rates; specific fan powers; heat recovery system efficiency; control settings; infiltration rate) and natural ventilation systems (maximum/minimum air change rates; infiltration rate; control settings e.g. temperature and carbon dioxide settings for automated control)

Space conditioning systems include thermostat setting (setpoint), capacity, efficiency, fan power and efficiency, pump rating and efficiency, chilled water inlet/outlet temperatures, hot water inlet/outlet temperatures, and terminal unit efficiency. Occupancy patterns and behaviour (schedules) include number of occupants, occupancy schedule, heating operation schedule, cooling operation schedule, mechanical ventilation operation schedule, natural ventilation operation schedule, lighting operation schedule, and equipment operation schedule.

The areas are compiled from a semi-structured literature review on sensitivity of building simulation models and analysis of performance gap root causes in different building types (BSI, 2008; Hopfe and Hensen, 2011; Manfren *et al.*, 2013; Yang and Becerik-Gerber, 2015; Faggianelli *et al.*, 2017). The areas that contribute to the performance gap are identified and validated on a case by case basis during the BPM calibration. All the independent inputs that are responsible for the performance gap are linked to one of the defect categories and areas. They form the SD array of interface parameters to the BPM (see Table 1 in Papachristos *et al*. (2020) for an example).

Each of the interface parameters uses a single numeric value to represent the percentage deviation of a defect area from its baseline value e.g. system efficiency values. This deviation is the baseline quality index to which the SD part is calibrated to (see section 4.1 in Papachristos *et al*. (2020) for an example). An extra step is therefore required to transform the single quality index the SD part generates into BPM input and vice versa for SD calibration. For example, all occupancy schedule values change with time, or occupancy density changes with zone functions. The transformation could involve the exposed surface area averages for fabric elements; zone area weighted average calculation for activity and load values, and day type or annual averaging for schedule type elements. An appropriate data processing technique should be used to ensure that all data is suitably transformed. Table 1 lists building defect areas and their corresponding percentage Quality Index Deviation from the ongoing exploratory case used for framework development[10]. For example, an area with lower operational performance relative to the design stage target is the *heating system efficiency*. In this case, the input parameter to the BPM is the Coefficient of Performance (COP) of the heating system.

[Table 1 near here]

The Quality Index Deviation values derived through the building physics analysis are used to calibrate the SD model. An assumption for SD calibration is that the strength γ of knock-on effects N_{ij} of defects from stage *i* to *j* per building performance area α is greater than one, in line with theory (Lyneis and Ford, 2007) and evidence (Parvan *et al.*, 2015). N_{ij} depends on the sum of undiscovered defects T_{ui} and known defects T_{Fi} normalized against the initial design scope T_{total} per building area per stage, and γ. The SD part is calibrated by optimising simultaneously γ for all building areas to minimise the performance gap error of SD output per building area α (see model calibration section in Papachristos *et al*. (2020)). Supressing α, N_{ij} is given by:

$$N_{ij} = (1 + (T_{ui} + T_{Fi})/T_{total})^{\gamma - 1} \tag{14}$$

The calibrated SD part is then used to explore a range of project management scenarios based on particular case characteristics. The scenario output is fed back to the BPM and building operation is

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[10] This is currently under submission and has been presented at International System Dynamics Conference 2018, Iceland.

simulated for a year to generate results for energy consumption for each fuel in terms of kWh, electricity and gas costs or costs associated with any other fuel used as a source of energy, CO_2 emissions related to energy use can also be calculated using CO_2 conversion factors for each fuel (kg CO_2/kWh). The conversion factors currently implemented in the UK are provided in BRE (2014, Table 12, p225).

Summary of building performance and system dynamics interface

The framework couples two modelling methodologies and requires substantial investment in time and effort to collect data, adapt and calibrate the models to a particular case and use them for analysis. Energy performance is used as the key performance metric for the description of the framework. In principle additional metrics such as IEQ can also be used as and when required, for a review see Lai and Man (2017). Figure 4 details the steps involved in the framework (as shown previously in Figure 1) and its application (Papachristos *et al.*, 2020). The framework application process starts with case project data and building analysis in a BPM to determine building defects and establish their underlying causes.

Case Project Input includes the performance gap between the real and design intent performance in a building case (Figure 4, step 1). The design intent is established from the final as-built BPM of the building, or documentation on input data and energy performance. For the real performance, a robust energy performance calibration protocol is selected, or defined, such as ASHRAE Guideline 14 (2014). When the building reaches its steady mode of operation post-occupancy, building operation data are captured for at least one full year with installed sensors and the Building Management System (BMS). The BPM is then calibrated based on these data. If the initial design model is not available, a new model is developed in a building modelling tool[11]. The building operation input data in the calibrated BPM part are compared against the design intents.

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[11] DesignBuilder software with EnergyPlus © as the simulation engine is the tool that our research team has significant experience in, but in principle any other tool could be used.

The output data of the BPM part are compared against the design intent performance model to establish the performance gap.

Part of the case project input are the *defects* and performance *deviations* in building areas, that are needed to determine the number of array elements required in the SD part (Figure 4, steps 2, 3). The building operation input data to BPM that may lead to underperformance can indicate *defects* in the execution of technical specifications or *deviations* of actual operating conditions from the design assumptions used (e.g. higher heating set point and longer occupancy hours). The calibrated BPM enables the identification of the technical *defects* and *deviations* in building operating conditions. It is critical for building experts to investigate and understand the *defect* root causes and to revisit the assumptions made for operational conditions in the underlying project construction process stages that led to *deviations*. For example, biased assumptions made in the design stage to lower energy consumption and ensure that certain energy and sustainability ratings are met.

The causes of identified technical defects and deviations in operating conditions can be generally first order: specific technical issues that directly caused the defect or issues that led to deviations in assumptions, or second order: underlying process issues that led to the first order issues. The causes are identified by: (i) a joint post-occupancy evaluation of the building with the design and construction teams and users, and (ii) an independent building performance evaluation to review the design and construction documentations, identify the performance gap causes in-operation, and establish the underlying issues. A hybrid approach is often used in practice where independent evaluators identify first order causes, and stakeholders are engaged via semi-structured interviews and workshops to identify second order causes.

The building experts can then provide evidence-based estimates on the contribution of each stage to final building quality (P_i) and the quality assurance thoroughness in each stage (H_j) based on the type of the contract, project official gateways, information available from design, construction, and commissioning documents, and feedback received from stakeholders (Figure 4, step 4). These estimates form part of the SD model input.

Adjustments to the SD model variables and/or structure may be necessary depending on the construction project characteristics and input from the experts or project stakeholders (Figure 4, step 5). Adjustments to the SD part require, each time, structural and behavioural validation based on empirical data in line with best practices in the SD field (Barlas, 1996; Sterman, 2000:843). The changes implemented to the SD part to adjust it to a project case can be documented to facilitate transparency (Rahmandad and Sterman, 2012; Martinez-Moyano and Richardson, 2013). Then the SD part is calibrated to the documented performance gap of the building areas (Figure 4, step 6).

The analysis of the performance gap provides insights into case specific scenario exploration of factors that may influence the performance gap (Figure 4, steps 7, 8) such as different CSC partner alignment, and different project control and rework. The SD part generates *Building Quality Indices* that are the input for the BPM to simulate operational performance and generate annual energy demand, cost, and CO_2 emissions (Figure 4, steps 9, 10) that are contingent on several factors (Ye et al., 2018)

[Figure 4 near here]

Discussion, Limitations and Future Work

The multi-methodology framework developed in this paper aims to explore the link between building quality and building performance, and between project partner relations and construction project performance. The integration and operationalization of project partner alignment and information flows in the SD part is a theoretical extension of the generic, multi stage project management model (Ford and Sterman, 1998a). The stock and flow structure can facilitate the assessment of project collaboration related effects on building operational performance and CO_2 emissions that are hampered by fragmentation in the UK and elsewhere[12]. Published results from the application of the framework to a UK case study illustrate the potential benefits of increased

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[12] The intended application context as part of the funded research project concerns UK and China.

alignment in the construction supply chain (Papachristos *et al*., 2020). If project partners and actors in the construction industry are incentivized to align more while they operate in projects then this would contribute to the low carbon transition in the construction sector.

The novel methodological integration of SD and BPM in a single framework enables the detailed assessment of operational building performance on a case by case basis. This is a useful extension for climate change mitigation that was missing in system dynamics and project management literature. The framework, thus, has the required theoretical generality and situational grounding, while being methodologically rigorous and practically relevant to both fields (Ketokivi and Choi, 2014).

The framework can function as a post-project review tool, or as an education and training tool for academics and practitioners. It can facilitate strategic learning for stakeholders involved in construction projects as it is done often with SD project management models (Lyneis and Ford, 2007). The added value is that the framework can facilitate the analysis of gains in operational building performance in terms of project performance analysis. The long-term aim is to produce research that will alter the way industry insiders and policy makers view CSC collaboration, so that CSC partners then consider seriously incentive mechanisms in procurement routes that permit sufficient, timely and accurate information for CSC governance to deliver gains in operational building performance. The aim is to inform relevant policy and regulations through case-based research, to increase the likelihood of successful carbon emission reductions and better IEQ, and thus to contribute towards the low carbon transition in construction industry.

Data availability on project time and cost will influence the application of the framework in the UK and elsewhere. The proposed modelling framework has certain case specific information requirements that may impact its intended use and successful application. First, limited access to key project stakeholders may compromise the assessment of project partner alignment and communication flows, of partner interactions across stages, and of possible adjustments to the SD for a specific building case. Second, the number of tasks for each building area in each stage has 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 depends on project partner access which can be a challenge 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 to account for resource constraints. 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.

Fourth, the identification and validation of the root causes of performance gap, and the defect areas, is based on analysis on the initial, calibrated BPM. The calibration criteria used in ASHRAE Guideline 14 are statistical indices and can also be met with changing BPM inputs that might not relate to the actual defect areas. It is important to validate the energy model calibration changes and the defect areas identified with onsite monitoring data and detailed technical reviews to avoid misjudgement on building defect areas.

Four potential future developments are envisaged for the framework. First, the introduction of partially defective tasks in the SD part to increase realism with respect to workarounds. They can be partially defective but may still support the functionality of the systems they are part of and pass quality assurance. Second, account explicitly for the flip side of workarounds: value engineering and potential partner conflicts that may arise around it. This will facilitate exploration of CSC collaboration and adversarial relation dynamics on project cost, time, quality and operational performance.

Third, the assumptions on partner alignment and partner aggregation in CSC stages can be explored in more depth. Model disaggregation is used often in system dynamics (Sterman, 2000:214-216), and it would require a more detailed 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 monitor and establish the characteristics of partner communication. The interview guides used should also be adapted to the needs of the research each time.

Fourth, project partner alignment could be unpacked to make it more relevant for policy making purposes. Future SD development could elaborate on the alignment and information sharing effect on project quality contingent on project novelty, size, complexity and difficulty, and unpack the absorptive, adaptive and restorative capacities of project partners (Yan and Dooley, 2013; Zhu and Mostafavi, 2017). This development will allow exploration of project complexity induced disruptions without sole reliance on expert estimates on the contribution of each stage to building quality and the level of testing thoroughness that implicitly account for this.

The exploration of alignment effects on building performance in the third and fourth points, could emphasize the importance of project governance and the mix of regulations, economic incentives, procurement routes, and information to improve performance (Williams and Samset, 2010; Samset and Volden, 2016). This would shift attention from project management and delivery per se onto the broader issues of the project’s benefits, utility, impacts and effects. To facilitate this kind of study the framework could be applied in a case with a focus on empirical validation of traditional vs design and build contractual arrangements to assess how different procurement routes would perform in a case. In this respect an interesting avenue of inquiry would be project budgeting (Kaka, 1994; MacSporran and Tucker, 1996; Lai, 2010), and embodied carbon emissions (Kahn et al., 2014).

Further development of the framework could explore the potential overlap and integration with Building Information Modelling (BIM), a methodology with technological, agential and managerial components (Oraee *et al.*, 2017). 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). BIM can facilitate the exchange of information and data between various stages of design, construction and building operation in support of the framework presented in this article. This is a fruitful direction for development as a systematic consideration of the managerial aspects of BIM-enabled sustainable design is missing in the literature (He *et al.*, 2017). For example, an issue is the lack of coordination among people, tools, deliverables, and information requirements.

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 construction industry and building performance to total CO_2 emissions, and related health effects (i.e. IEQ). Meeting the emission reduction targets set by most developed and developing nations requires significant emissions reductions across all sectors, including construction. This implies a transition, a radical shift in construction practices, and knowledge at the project level. This requires a framework that facilitates the analysis of the management process of new building development projects, and the subsequent in-depth 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 framework is of particular benefit in building project contracts that include building performance targets.

The project management SD part of the framework integrates three behavioural concepts of project operations management: partner alignment, coordination and information sharing. They account 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, 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, the model can be used to explore project governance interventions that span the alignment, coordination and information sharing among project partners. Simulation results can provide a detailed picture of project governance effects on operational building performance, through the interface with the building performance model.

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 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. The modelling framework is a first step to explore this effect in detail. Future research should seek to apply this framework to construction projects and develop insights for policy making.

Data Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability statement

Data available on request from the authors

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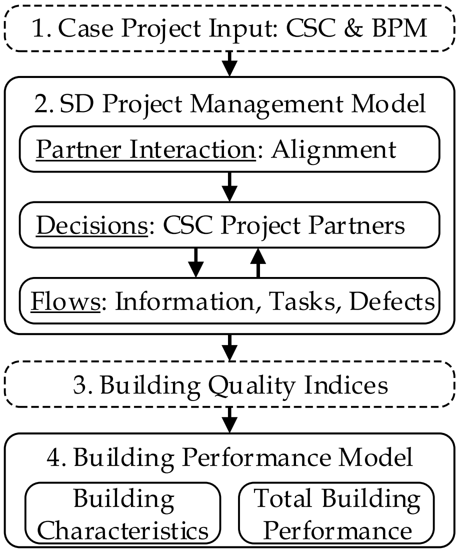

Figure 1 The multi-method modelling framework

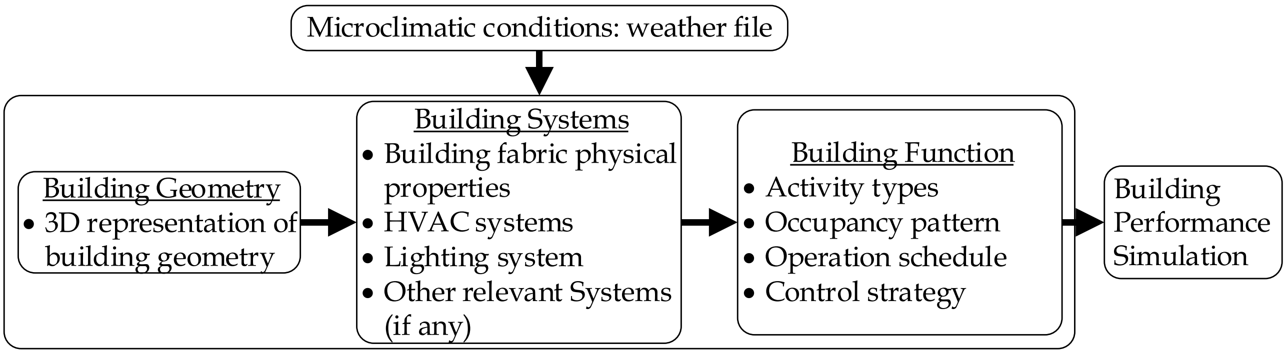

Figure 2 Overview of BPM process

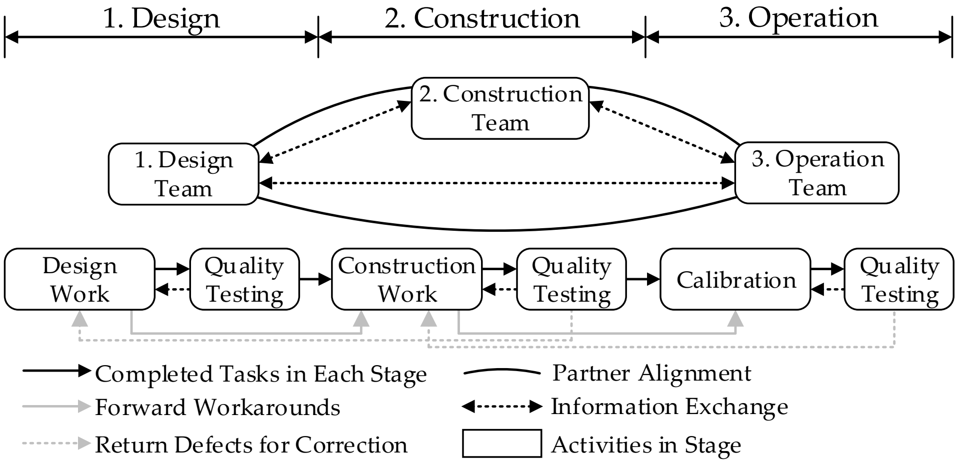

Figure 3 Conceptualization of project stage physical flows between design and construction stages

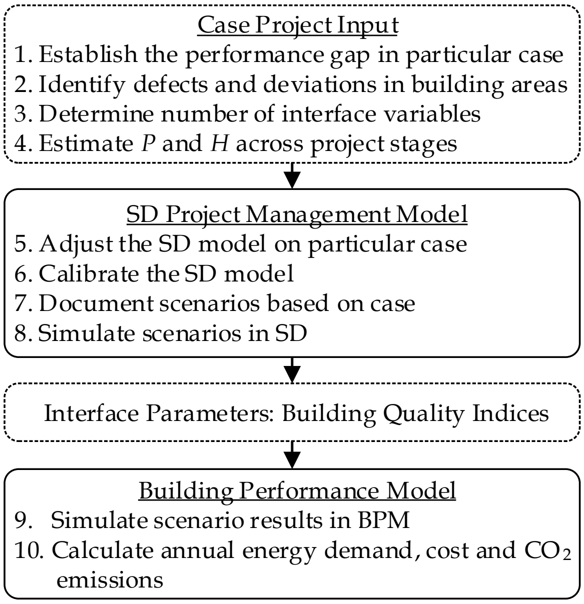

Figure 4. Overview of framework application steps

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

SD Array Element	Building Area	BPM Input	Actual Building Defect	Remarks	Quality Index Deviation
1	Heating System Efficiency	COP value of heating system	Undersized heating terminals, inadequate heat exchange surface area in hot water buffer vessels	COP parameter represents the aggregated system performance	0.17
2	Lighting power density	Lighting load per unit area	Increased lighting loads than designed	Direct Input Parameter	0.6
3	Office equipment power density	Office equipment load per unit area	Increased small power loads than designed	Direct Input Parameter	0.25
4	Ventilation	Ventilation Control: Maximum CO_2 Concentration	Faulty sensors in the building leading to increased CO_2 concentration	The defect in the sensors can be represented by artificially changing the maximum CO_2 concentration control.	0.50
5	Occupancy hours	Occupancy Schedule hours	Building used for longer hours than designed	Direct Input Parameter	0.81