Low carbon building performance in the construction industry: A multi-method approach of project management operations and building energy use applied in a UK public office building

Abstract

The “performance gap” in the United Kingdom construction industry is a persistent problem as new building development projects underperform more often than not. The “performance gap” is partially attributed to the number of stages involved in building project development and the coordination difficulties of partners with different incentives. The project outcome is important for energy consumption, carbon emissions and occupant well-being. Thus, it is important to study the project management process in terms of the standard time, cost and quality parameters, but also in terms of project partner incentives and coordination, and the subsequent energy performance and resultant indoor environmental conditions. A system dynamics model of project management processes is developed to explore the implications of partner coordination for building quality. The system dynamics model is coupled to a building performance simulation model to explore building energy consumption and Indoor Environmental Quality, and apply this on a recent building project case study. Results show that greater project partner alignment can reduce annual energy consumption up to 12% and CO_2 emissions up to 37%, with greater emphasis in the design stage of the project subject to resource availability. The trade-offs involved on value appropriation are considered and discussion of results points to possible ways for improvement.

Keywords: energy consumption, simulation, low carbon, building performance, system dynamics

Abbreviations

IEQ : Indoor Environmental Quality

CSC : Construction Supply Chain

SD : System dynamics

DEC : Display Energy Certificate

D&B : Design and Build

1 Introduction

The construction sector, which includes residential and commercial structures, accounts for almost 21% of the world's delivered energy consumption (EIA, 2017). In the European Union, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2018). Urgent and ambitious measures are required for performance standards in new and retrofit buildings (IPCC, 2014). In 2009, the UK government set a target of at least 80% total emissions reduction by 2050. This target requires greater reductions of building energy use and emissions (Oreszczyn and Lowe, 2010). Such reductions must also not generate unintended consequences in terms of indoor environmental quality (IEQ) and other performance metrics (Davies and Oreszczyn, 2012; Shrubsole *et al.*, 2014).

Reaching the UK CO_2 targets cannot depend only on combinations of current technologies and new ones, or a continuation of current trends in the construction sector (Lowe, 2007). Construction project performance improvements could be achieved through greater integration, and operations coordination between project partners (Turner and Müller, 2003). The need for such improvements in the historically fragmented UK construction industry has been highlighted by government reports (Latham, 1994; Egan, 1998). Since the publication of the reports, CSC collaboration has increased in operations practices of the UK construction industry and the energy performance of the existing non-domestic building stock has improved (Meng, 2013). Nevertheless, performance gaps remain between the intended and actual performance of new and refurbished buildings (Cohen *et al.*, 2001; De Wilde, 2014; Committee on Climate Change, 2014). Given the 2050 target of carbon emissions reduction in all industrial sectors, a highly pertinent research question for the construction sector that motivates the current research is whether it is possible to achieve further building performance improvements through collaboration in construction project management operations?

In an attempt to address this question, the focus analysis ofon physical project work must be complemented with a focus on CSC project partner collaboration, industry fragmentation effects, and operational building performance. The behaviour and interactions of construction supply chain (CSC) partners in design, construction and operation project stages influence also the building quality, long-term energy consumption, and Indoor Environmental Quality (IEQ) (Bendoly and Swink, 2007; O'Brien et al., 2009; Alencastro et al., 2018; Gram-Hanssen and Georg, 2018; Shrubsole et al., 2019). SD research has produced an appropriate, generic project management model structure that is geared to tackle a class of problems rather than a single case (Forrester, 1961; Ford and Sterman, 1998; Han et al., 2013). However, recent modelling and simulation work on construction project management (Rahmandad and Hu, 2010; Han *et al.*, 2013; Parvan *et al.*, 2015), reflects the perception of client value in the construction industry in terms of delivering high quality buildings on time and within budget (Atkinson, 1999), and does not explore the direct implications of CSC on operational building performance and IEQ. However, this is 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) (Bendoly and Swink, 2007; O'Brien et al., 2009; Alencastro et al., 2018; Gram-Hanssen and Georg, 2018; Shrubsole et al., 2019).

The typically short-term nature of projects (Turner and Müller, 2003; Geraldi et al., 2011), requires an analysis from a behavioural perspective where project management agents use decision rules with emphasis on CSC integration, and short term reaction to short term feedback, rather than anticipation of long-term strategies (Cyert and March, 1963; Bendoly and Swink, 2007; Gavetti et al., 2012). However, operational building performance models do not facilitate analysis in terms of CSC project management processes, so few studies assess the impact of poor quality management and defects on the energy performance of buildings (Alencastro *et al.*, 2018).

The broad link of construction project management to building performance and in particular to environmental sustainability performance is still largely missing, but this link is becoming increasingly relevant and necessary (Huemann and Silvius, 2017; Silvius, 2017) [1]. This paper seeks

[1] Special issue in International Journal of Project Management

to address, explore and document potential solutions to this problem (Holmstrom *et al.*, 2009). A novel modelling framework is developed that seeks a sense of theoretical generality while being situationally grounded, methodologically rigorous, and practically relevant (Ketokivi and Choi, 2014). It is the first attempt to bridge project management and building science simulation methods in a multi-methodology framework (Mingers and Brocklesby, 1997). System dynamics (SD) is used for case-based research (Papachristos, 2012) on project management (Sterman, 2000; Williams, 2002; Lyneis and Ford, 2007; Mingers and White, 2010), and supply chain collaboration modelling (e.g. Adamides et al., 2012; Papachristos and Adamides, 2014), and building physics modelling for building performance simulation (Hensen and Lamberts, 2011).

The framework integrates the behavioural and technical aspects of project management (Bendoly and Swink, 2007), and is applied to case specific research on building performance of a recently completed public office building in UK. Through seven hour-long, semi-structured interviews, followed by a dedicated workshop with project stakeholders, it became clear that the case has a number of characteristics that make it an appropriate choice to demonstrate effectiveness (Yin, 2003): (i) The building energy performance target was set at 'A' as defined by the Display Energy Certificate (DEC), placing it in the top 15% of public office buildings in UK. (ii) The project followed a Soft Landings approach, which aims to improve operational building performance in post commission (De Wilde, 2014). (iii) Project partner alignment and commitment was recognized as above normal by project stakeholders, who further considered the resultant building and construction project to be exemplary in terms of energy and IEQ performance.

The introduction described the research objective, theoretical and practical justification, context and approach taken for the current research, the rest of the paper is structured as follows: Section 2 describes the data and provides an overview of the case building. It then describes the principles of Systems Dynamics as relevant to this application. Section 3 presents the Systems Dynamics Model and its elements as related to the case. It also presents the novel hybrid model that comprises system dynamics model coupled to the building performance model. Section 4 presents results of applying this novel model and explores the effect of project operations factors. Section 5 discusses implications, limitations and future research and section 6 concludes the paper.

2 Data and Method

2.1 The Building Case

The building is a recently completed UK public office with 4 storeys, designed for 450 staff. The building is intended for long term use and the client has a vested interest to achieve low operational use costs. The target of the project is to achieve a Display Energy Certificate (DEC) A rating which is part of the contract (without an explicit IEQ target). The project is the first to follow a four-year, Soft Landings approach where project partners try to improve building energy performance (De Wilde, 2014). Detailed building performance monitoring and analysis through modelling show that the building is close to but has not yet reached DEC A performance, three years after its commission. It has received several industry awards and wide publicity with a stream of sustainability themed tours around the building attended by a variety of industry professionals.

The project used a design and build (D&B) procurement route that requires substantial client involvement in the early design stage to determine the core concept of the project before inviting competition from D&B contractors for construction. The client involvement contributed to a clear goal statement that generated CSC partner alignment. D&B vests authority and responsibility for design and construction with a single contractor from initial briefing to the delivery of the building (Molenaar *et al.*, 1999). The contractor takes over the design from the client's concept design team, develops the detail design and constructs the building.

Detailed knowledge about the case study building was developed by two research team members with construction industry experience. 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. This provided the basis to assess building performance issues. Additional interviews were conducted with seven industry experts (see Appendix A for interviewee profiles). The experts confirmed that a strong client focus on building energy performance is still a niche market. Five experts were partners in the building project and also went on to participate in a focused workshop that provided the opportunity to juxtapose the content of their interviews with the retrospective discussion about project aspects. A consensus view formed around six points regarding aspects of collaboration:

1. Partners perceived the building as a flagship project: *"…the reward of being the first team that has planned and delivered a DEC A project would be really significant…".*
2. The project provided an opportunity to enhance their industry reputation because the building would function as a *"...sustainable design beacon of excellence…".*
3. Partner alignment and commitment was substantial, as the director for sustainable architecture and research of the architect firm stated they viewed the project as *"a research project, throwing all our research resources at it.".*
4. Prior partner collaboration was one of the reasons for collaboration in this project as well. The confidence that partners could deliver quality work was evidenced by the architect firm director: *"the line was: this is really a job for…"* in reference to the main contractor firm.
5. The client: *"wanted more certainty on operating costs"* because the building was intended for long term use. This provided a strong incentive and partner alignment with the client to achieve high building energy performance.
6. The project outcome is regarded as *"...enormously better than it would have been if we hadn't been through the process that we went through".* The client facility manager echoed this view, as the current operational cost savings are significant *"...six or seven times"* less compared to costs in the building the client occupied previously. The additional budget required to cover for building underperformance *"...is very small compared to other pressures"* the client faces.

2.2 Method

A modelling framework was developed to facilitate analysis of the relation between CSC operations and operational building performance. The framework has been designed to explore retrospectively project development and total building performance, and identify ways to improve it. It adopts a flow view of production in CSCs (Vrijhoef and Koskela, 2000). The core structure of the project management model draws on prior system dynamics work that has been extensively validated through the successful application in a range of areas (Ford and Sterman, 1998; Parvan *et al.*, 2015) [2]. It involves three common, core project structures (Cooper *et al.*, 2002): (i) project task workflows and the corresponding flows of defects[3] and rework that arise in the project, (ii) decision feedback effects on workflow productivity and quality, and (iii) knock on effects from upstream to downstream stages.

The framework involves *Case Project Input* on CSC operation data (Figure 1): project timing, resources, stages, and organizational aspects. Input involves also building performance data for which a building performance analysis is done with a *Building Performance Model* (BPM). The analysis identifies the building areas where known operational building performance deviates from design targets, a widely applied definition in the UK (Cohen *et al.*, 2001). The SD model uses the *Case Project Input* to generate *Building Quality Indices* for the building areas where known operational *Total Building Performance* deviates from design targets. This is the input to the BPM. The assumption in coupling the two models is that building quality can be used as a proxy for building performance (Alencastro *et al.*, 2018). The SD model is then used to explore scenarios that could result in better building quality and thus *Total Building Performance* i.e. energy consumption and IEQ. The following sections develop the core SD model elements and its interface with the BPM.

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[2] The detailed working paper version of Ford and Sterman (1998) was used: https://dspace.mit.edu/bitstream/handle/1721.1/2644/SWP-3943-36987273.pdf?sequence=1 (accessed 01/06/2018)
[3] 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.

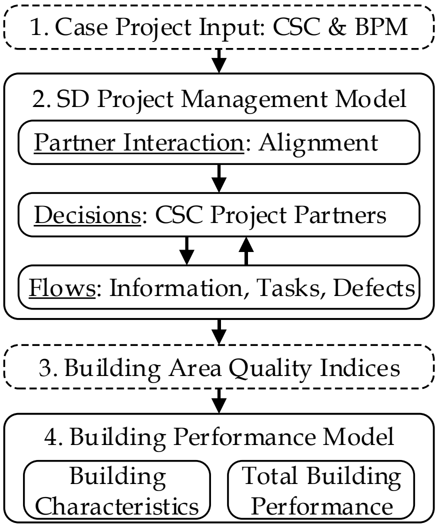


Figure 1 The modelling framework combining project management and building performance

2.3 System Dynamics Model Conceptualization

Project management research is one of the most successful SD application areas (Cooper, 1980; Abdel-Hamid, 1984; Ford and Sterman, 1998). Some SD work has focused explicitly on construction projects (Rodrigues and Williams, 1998; Park and Peña-Mora, 2003; Rahmandad and Hu, 2010; Parvan *et al.*, 2015). Lyneis and Ford (2007) and Han *et al.* (2013) provide an overview of the evolution of the core SD research and project management model structure.

In real CSCs many partners operate and interact in and across project stages, through physical and information project flows. The SD model is based on a simplified CSC that aggregates partner organizations at the project stage (Love *et al.*, 2004). The CSC consists of design, construction, and operation stages, each representing aggregate partner with a remit of responsibilities, task and information flows, and partner alignment within and across stages (Figure 2).

CSC task flows are based on Ford and Sterman (1998). Tasks are subject to *Quality Testing* at each stage to find defective tasks that lower building quality. Defects are reworked in-stage or returned upstream through inter-stage flows. An extension on Ford and Sterman (1998) is introduced to increase model realism in line with construction practices. An additional task flow is used to account for workaround flow to downstream stages (Morrison, 2015; Aljassmi *et al.*, 2016). Project partners may choose to do workarounds and “patch” construction issues onsite without consulting with designers due to time pressure, or other limitations. Workarounds compromise quality because quality assurance and/or other standards are often not followed. Information flows are important for supply chain performance as partners exchange information in- and between stages to monitor delivery of work and quality and guard against opportunism (Lee *et al.*, 1997; Turner and Müller, 2003). Finally, partner alignment facilitates CSC performance as partners align around goals and share an understanding of how these can be achieved in the project.

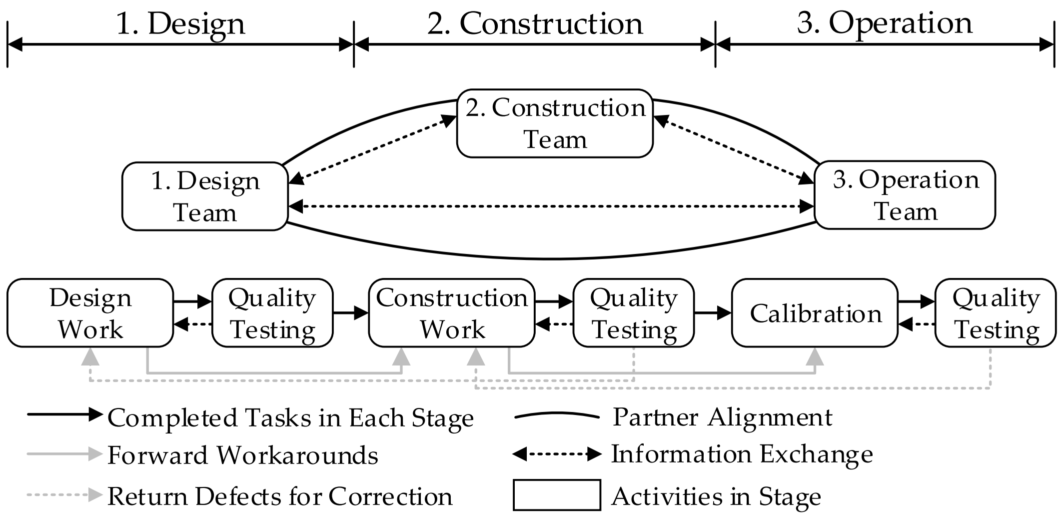


Figure 2 Conceptualization of project stage physical flows between design and construction stages

The conceptual CSC is formalized in an SD model. Figure 3 (left) shows the core structure of the model. On the left are the stocks (boxes) and flows for tasks in a stage (the design stage does not have the *Task Return Upstream Rate*). The flows in light grey depend on the level of CSC partner cooperation. On the right is the co-flow structure implemented to track defect flows in a stage (Sterman, 2000). Defects can have knock-on effects on the work quality of downstream stages and trigger further rework that lead to variability in project performance, quality and cost (Ford and Sterman, 1998; Lyneis and Ford, 2007).

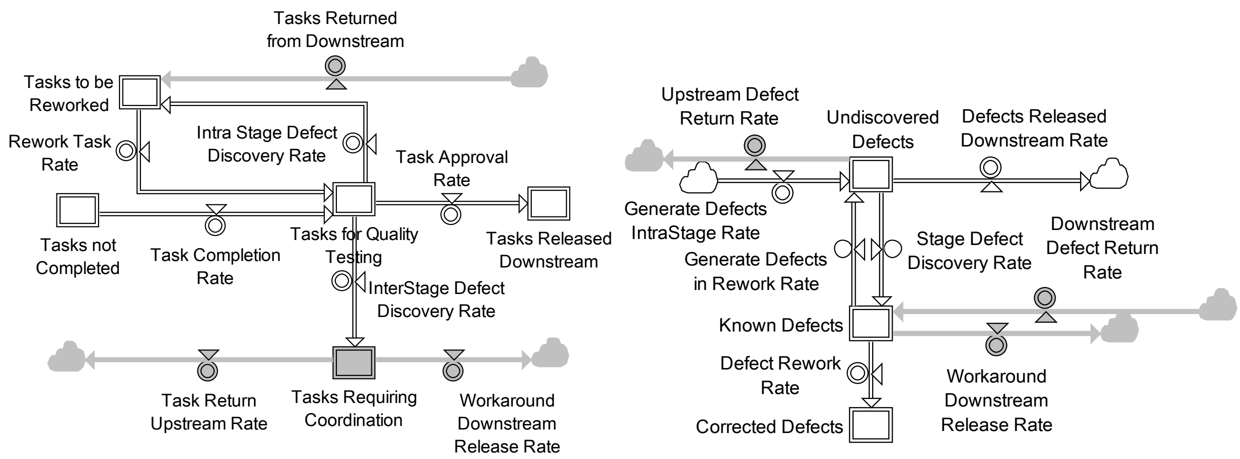


Figure 3 Core stock and flow structures in the SD model: for tasks (left), for defects (right)

The client requirements on time, cost, quality, *and* energy performance, and their inter-relations increase building project complexity (Baccarini, 1996; Dooley and Van de Ven, 1999; Baskhi *et al.*, 2016). The extensive use of subcontractors in UK building industry increases CSC fragmentation and project complexity effects that can lead to low understanding of project dynamics and low performance (Vrijhoef and Koskela, 2000; Bendoly, 2014; Papadonikolaki and Wamelink, 2017). Project performance suffers as project partners may not share the same understanding about project scope and inter-organizational relations that 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).

High project performance requires CSC integration, coordination and alignment of partner goals (Gulati *et al.*, 2005). Alignment and coordination are important in the delivery of high-quality buildings as they moderate workflow control and CSC coordination. Goal alignment creates shared interests across partners and increases their cooperative behaviour and communication (March and Simon, 1958; Jap and Anderson, 2003). Communication of partner ambitions, design intent and responsibilities may increase project performance and reduce the performance gap (De Wilde, 2014). It is necessary to account for their effects in SD model development.

3 System Dynamics Model Development

The SD model was developed in close collaboration with two of the authors with building industry experience that provided sanity checks throughout model development[4]. The key model parameters discussed in sections 3.1–3.3 are partner alignment in the process of project development, the flows of project work and rework through the construction supply chain, and building quality that represents the outcome of the project process (for more details see Papachristos et al. (2018a;b;c)).

3.1 Partner Alignment

Organizational alignment research spans the strategic management, supply chain management and project management literatures, and links strategy, organizational activities, and competitive advantage (Powell, 1992; Williams and Samset, 2010; Hanson *et al.*, 2011; Wong *et al.*, 2012; Samset and Volden, 2016; Adner, 2017). Partner alignment requires clear cause and effect mechanisms, a strategic goal consensus, and operational level actions and behaviours towards a final outcome. Alignment applies to single organizations but it can extend across CSCs and arise out of the configuration of interorganizational CSC relationships that involve partners, clients and suppliers (Briscoe *et al.*, 2004; Vachon *et al.*, 2009; Samset and Volden, 2016). The level of CSC alignment depends on organizational performance, partner motives, top management support, a consistent understanding of partner relations, actions, material and information flows that deliver client value (Hanson *et al.*, 2011; Wong *et al.*, 2012; Adner, 2017).

Interorganizational relations develop with time through joint value-creation project processes (Ring and Van de Ven, 1994). Projects are temporary organizational entities that dissolve eventually but they remain embedded in the senior management memory of partner organizations which are enduring entities. Thus, project partner expectations arise and depend partly on whether partner expectations were met in previous projects (Zaheer *et al.*, 1998; Molenaar *et al.*, 1999; Laan *et al.*, 2011). Prior joint efforts generate a common understanding of partner goals and ways to

[4] The complete list of SD model equations is in Appendix E. The SD and building physics models are available upon request from the authors.

coordinate when organizations undertake new joint projects (Tsai and Ghoshal, 1998; Gulati *et al.*, 2005) as was illustrated by the project architect firm director: *"…the line was: this is really a job for…"* in reference to the main contractor firm. Such an understanding can facilitate information sharing, CSC partner alignment, coordination, and problem resolution (Hong *et al.*, 2004; Browning, 2010; Dietrich *et al.*, 2010; Bendoly, 2014).

In the model, an initial level of intra-stage alignment A_i^o, existed between project partners and was elicited from interviews and the workshop (see Appendix B). Alignment may develop with time as partners make sense of the project, work towards its delivery, and cope with 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 as partner participation nears its deadline D_i and other projects become more pressing, or with partner conflict. Suppressing time subscript t for clarity, A_i is given by:

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

The project stakeholder workshop provided evidence for an initial level of inter-stage alignment A_{ij}^o between stage i and j as project partners had a history of prior collaboration and they aimed to deliver a high-performance building. A high level of A_{ij} implies that CSC project partners are willing to receive and rework defects from downstream stages to improve the overall building quality. It is assumed that intra-stage partner actions are considered in subsequent reciprocal behaviour (Bendoly and Swink, 2007), thus A_{ij} increases with A_i and A_j:

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

Alignment enables coordination and information sharing to improve problem solving and handle disputes, reduce defects and rework, and increase CSC performance (Hoegl and Gemuenden, 2001;

Briscoe *et al.*, 2004; Dietrich *et al.*, 2010; Baiden and Price, 2011; Suprapto *et al.*, 2015). Partner interactions are generally coordinated by contracts but they can be influenced by information and behavioral attributes e.g. trust (Heide and Miner, 1992; Love *et al.*, 2002; Ford and Sterman, 2003). Trust can facilitate coordination among CSC partners and information exchange for problem resolution (Zand, 1972; Mayer *et al.*, 1995). Information exchange is important because it enables coordinated responses to unanticipated events, a common occurrence in projects with high task variety (Daft and Macintosh, 1981; Cohen and Bailey, 1997; Bendoly and Swink, 2007; Wong *et al.*, 2012; Bendoly, 2014).

Information is essential to reduce uncertainty, complete tasks, coordinate and handle issues, and deliver client value (Tushman and Nadler, 1978; Daft and Macintosh, 1981; Hoegl and Gemuenden, 2001; Atkinson *et al.*, 2006; Meng, 2012; Jingmond and Agren, 2015). Project partners with a shared understanding of project dynamics are more likely to appreciate the value of information and share it (Bunderson, 2003). Failure to appreciate the criticality of information flows among stages and their effects, can lower communication levels, information quality and increase project rework (Love *et al.*, 2008; Tribelsky and Sacks, 2010; Jingmond and Agren, 2015).

Project information flows can be complex (Baldwin *et al.*, 1999). In the model, inter- and intra-stage information flows are simplified and alignment influences them once partners engage in project tasks. It is assumed that a unit piece of information is required to perform a unit task without any defects (Ford and Sterman, 1998), so the completion of a building area requires a maximum number of tasks per project stage and an associated maximum number of units of information I_i^{max}. It is assumed that intra-stage communication flow C_i increases with A_i and E_i per month Tribelsky and Sacks, 2010). C_i is given by:

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

The amount of change in project understanding relates to the amount of shared information I_i between stakeholders (Daft and Macintosh, 1981). I_i is defined as the stock of information that is gathered and interpreted by organization participants. Information tends to become outdated as the project progresses i.e. information has a half-life (Samset and Volden, 2016). It is assumed that intra-stage information I_i accumulates with C_i (Tribelsky and Sacks, 2010), and erodes inversely proportional to A_i, and D_i which is determined by the project timeline (see Appendix C). I_i is given by:

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

The reciprocal nature of inter-stage communication between C_{ij} stages *i* and *j* suggests a multiplicative relation that increases with A_{ij}, C_i, and C_j. 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} is assumed to behave in a similar way to I_i (Tribelsky and Sacks, 2010). I_{ij} depends on C_{ij}, and D_i and is given by:

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

3.2 Project Work, Control and Rework

The project work formulation follows Ford and Sterman (1998). Project rework is work that has to be repeated and arises from project defects or from client requirement changes (Love and Edwards, 2004; Lopez *et al.*, 2010; De Wilde, 2014). The number of defects can vary from very few to many hundreds, and it is a widely used quality indicator (Alencastro *et al.*, 2018). The quantity of rework in each project stage is inversely proportional to the quality of corresponding information stocks, which is assumed to increase with I_{ij} (Tribelsky and Sacks, 2011). It is assumed that the defect generation rate G_i in stage *i* depends on the task completion rate R_i, the stage contribution P_i to defects, I_{ij}, and the total number of tasks per building area T_{total} (Ford and Sterman, 1998). Tasks are assumed to be small enough to be defective or correct but not partially defective (Ford and Sterman, 1998)[5]. G_i is given by:

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

The intra-stage defect discovery rate F_i in stage *i* depends on the number of completed tasks to test T_{Fi}, the level of defect testing thoroughness H_i, P_i, and the resources for quality assurance test Q_i. Partner resource build up in every stage follows Ford and Sterman (1998). F_i is given by:

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

Defects in stage *i* are often detected in later stage *j*, where they have some knock-on effect (Sommerville, 2007; Aljassmi and Han, 2013; Alencastro *et al.*, 2018). Defects discovered in stage *j* depend on the proportion of defects to tasks P_{ij} that flow from stage *i* to *j*, and the proportion k_j of defects possible to rework in stage *j*. F_{ji} is given by:

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

It is assumed that I_i and I_{ij} can increase quality testing thoroughness H_j, and defect discovery (Tribelsky and Sacks, 2011):

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

Where H_{Oj} is the initial testing thoroughness level. Defects discovered in each stage may not be corrected due to partner resource constraints, and this makes likely the use of workarounds (Love *et al.*, 2002). The resource shortage effect follows an s-curve[6] and is modelled with a standard logistic

[5] This assumption also becomes more accurate as task size becomes smaller.
[6] Macleamy, P. (2004). Collaboration, Integrated Information, and the Project Lifecycle in Building Design, Construction and Operation. The Construction Users RoundTable. https://kcuc.org/wp-content/uploads/2013/11/Collaboration-Integrated-Information-and-the-Project-Lifecycle.pdf (accessed 31/05/2018)

S_j with value range (0..1) for each stage j (Sterman, 2000). The intra stage defect rework rate is based on Ford and Sterman (1998)[7] and is multiplied by $(1 - S_j)$ to account for resource related constrains. The inter-stage defective task return rate R_{ji} from stage j to i depends on k_j, A_{ij}, and S_j. R_{ji} is given by:

$$R_{ji} = A_{ij} \cdot T_{Fij} \times (1 - S_j)/t_{ji} \tag{12}$$

Where t_{ji} is the return delay from stage j to i.

3.3 Interface with the Building Performance Model

The SD model generates one quality index per building area, with identified performance issues, that represents the performance deviation from design stage operational quality targets. The index is directly proportional to the ratio of residual defects per building area over T_{total} and they are the basis for the interface with the BPM[8]. The number of building areas is determined through a BPM analysis and an array in the SD model is used to track the task and corresponding defect flows number per building area.

Two research team members with building industry experience developed the BPM of the building based on their knowledge and the interviews they did with project partners. As a result they provided estimates for the SD model on H_j and P_i (Appendix D). They pointed to performance issues in nine building areas that range from IEQ performance (related to ventilation in Table 1) and energy performance. For example, heating system efficiency is lower due to the under sized heating terminals and malfunctioning heat pumps (Table 1). In this case, the SD quality index represents the aggregate effect of the heating system issues on building performance, and it is used as BPM input for the heating system parameter: Coefficient of Performance (COP)[9].

[7] 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 (accessed 31/05/2018)
[8] A simplified, validated version of the building performance model is used to reduce computation time (approximately 24 hours for a single run)
[9] The tool used is DesignBuilder software with EnergyPlus © as the simulation engine.

Table 1 Identified performance building areas with performance issues in the case building

SD Array Element	Building Area	BPM (Energy Plus Input)	Actual Building Defect	Remarks
1	Heating System Efficiency	COP value of heating system	Undersized heating terminals, issues with heat exchangers in hot water vessels	COP represents the aggregated system performance
2	Lighting power density	Lighting Load per unit area	Increased lighting load than designed	Direct Input
3	Office equipment power density	Office Equipment Load per unit area	Increased small power load than designed	Direct Input
4	Occupant density	Number of People per unit area	Increased number of people than designed	Direct Input
5	Heating Set point	Heating system Set point	Building operating at higher Temperatures than designed	Direct Input (set point maintained during occupied hours)
6	Occupancy hours	Occupancy Schedule	Building used for longer hours than designed	Direct Input (hours of weekday occupancy changed).
7	Infiltration	Infiltration Rate	Manually operated vents not shut always/properly	Direct Input
8	Ventilation	Ventilation Control (CO_2 Concentration)	Faulty sensors in the building leading to increased CO_2 concentration	Sensor defects can be represented by changes in CO_2 concentration control.
9	Operation of HVAC System Pumps	Operation Schedule (Pumps/Vents)	Building pumps and vents used for longer hours than designed	Direct Input (annual average of hours of operation each day)

4 Model Simulation

4.1 Model calibration

The SD model uses the following inputs: (i) P_i and H_i for each stage per building area, (ii) work concurrency in, and between stages[10], (iii) stage resource constraints S_i, (iv) the proportion k_j of upstream defects that are reworkable in stage j, (v) performance gap figures per building area, and (vi) the level of A_i^o and A_{ij}^o. Appendix D provides tables for (i), (ii) is set to 90% based on expert judgement so that 90% of stage related work has to be completed for downstream stage work to begin, (iii) is set through expert judgement (see Appendix B), (iv) is set to 0 based on expert judgement, (v) was provided by building performance analysis (Jain *et al.*, 2017), and (vi) was elicited through project partner interviews and the workshop. The number of tasks for each building area T_{total} is set to 100. Initial I_i and I_{ij} are set to zero. Simulation time is five years.

[10] For concurrency relations see Figures 6-8 in Ford and Sterman (1998).

For the calibration of the SD model, it is assumed that knock-on defect effects between stages have a greater than unit effect (see Appendix B), in line with theory (Lyneis and Ford, 2007) and industry evidence (Parvan *et al.*, 2015).

4.2 Simulation Results

The SD model was subject to a range of standard tests to ensure model validity (Sterman, 2000, p859). For example, the SD model has been tested to confirm that it can reproduce a range of empirically derived behaviour patterns of building quality over time (e.g. Figure 1 in Bunn and Burman (2015)). Next, the SD model has been extensively tested across the range of expert input to understand the impact of each of its parameters. The input space of all possible estimate combinations for P_i and H_i was explored in 729 runs. Figure 4 (left) shows SD output of building quality indices with a min-max range for all areas (shaded grey bars) that envelopes the real area performance deviation (black line) from design performance. Figure 4 (left) results are the input to the BPM to generate annual operational performance results (Figure 4, right). Performance based on expert 1 best estimates lies on the minimum, because he provided input for 8 out of 9 building performance areas (Appendix D)[11], so the total building performance is better for part of the simulated year.

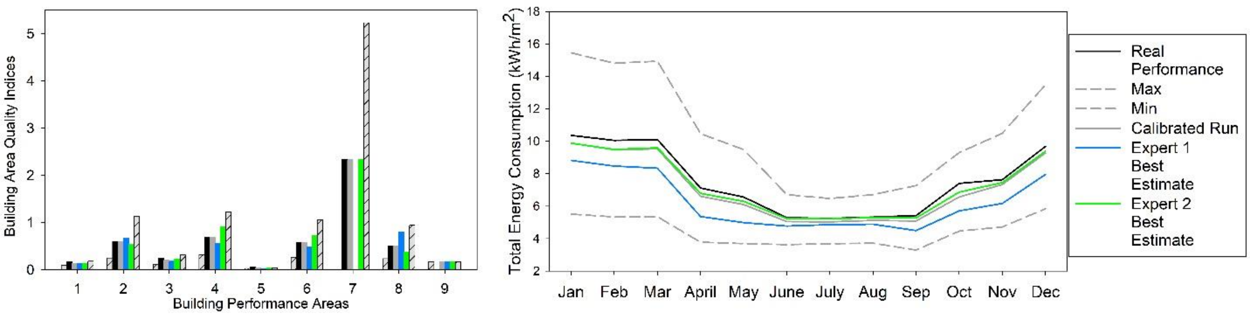


Figure 4 Simulation results for building areas with underperformance in Table 1: SD (left), BPM (right)

[11] Expert 1 did not provide estimate for area 7 because he did not have access to the calibrated model for the case building. The calibrated run uses best estimate inputs from expert 2 for area 7.

4.3 The Effect of Partner Alignment on Performance

The effect of initial partner alignment on building area quality was tested to explore the implications of UK report suggestions (Latham, 1994; Egan, 1998). Raising intra- and inter-stage initial partner alignment from zero to one (see Appendix A: Model setup for the scale interpretation) produces a 6.29% increase in average building quality and an increase from the reference input value of 0.5 to one improves quality by 5.73% (Figure 5, left). The corresponding figures without S-curve resource constraints are 18.59% and 9.97% respectively. Tests to isolate the effect of inter-stage, initial partner alignment (dotted lines) show that an increase from 0.5 to one would improve quality by 0.3%, and 6.32% respectively without resource constraints.

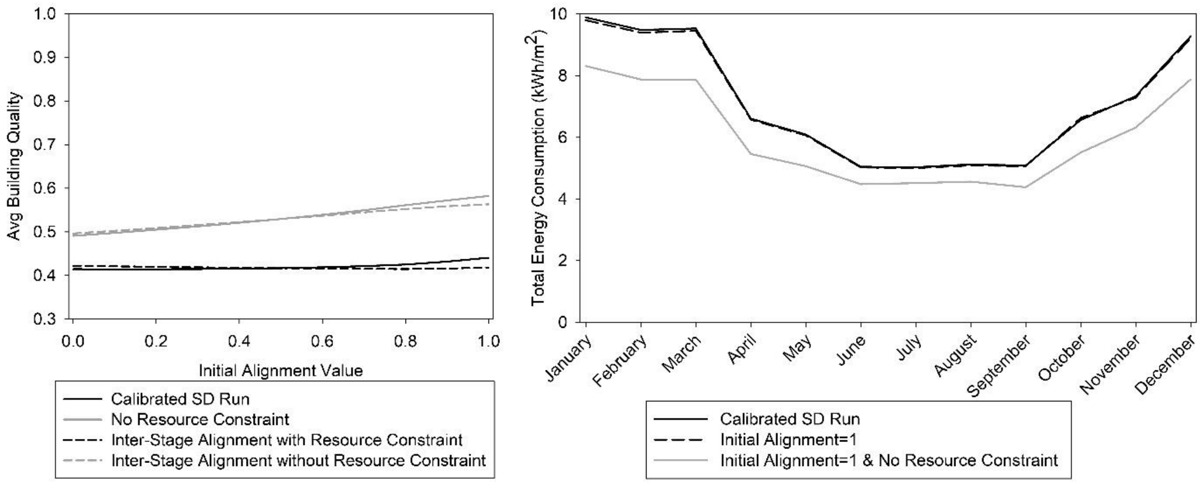


Figure 5 The effect of initial alignment and resources on: building area quality (left) and building energy consumption (right).

Building energy consumption reduction (Figure 5, right), generates energy cost and average CO_2 emissions reductions (Table 2). An initial alignment value of 1 with resource constraints reduces total annual energy cost by 0.67% and CO_2 emissions by 0.59% relative to the calibrated SD run. Without resource constraints these figures are 11.98% and 12.7% respectively. These figures may seem small because the real operational building performance is already high. The 12.7% CO_2 emissions reduction would improve the DEC rating to 31 which is consistent with the independent

BPM analysis that showed that the building could reach a DEC B rating of 30.5 at best with all technical issues resolved (the threshold for DEC A is 25).

Table 2 Annual building energy cost and CO_2 emissions (for UK specific, CO_2 conversion factors see Table 12, p225 in BRE (2014))

Building Performance % Change to Calibrated SD Run	Initial Alignment=1 Resource constraint	Initial Alignment=1 No resource constraint
Total Annual Energy cost % (£/m^2)	-0.67% (8.87)	-11.98% (7.86)
Total Annual CO_2 emissions % (kg/m^2)	-0.59% (36.78)	-12.7% (32.3)

Higher initial alignment and the removal of resource constraints increase performance and total task work due to rework relative to the reference run (Table 3). Rework in design and construction stages increases because project partners are more willing to receive downstream defects and they avoid workarounds to deliver higher building quality. As a result, rework at the operation stage is slightly reduced in both scenarios. The removal of resource constraints results in relatively less rework in design and illustrates that commitment to get things right first time around reduces workarounds and downstream stage returns.

Table 3 The effect of alignment and resource constraints on work done across stages relative to reference run

Project Work % Change to Reference Run	Initial Alignment =1	Initial Alignment =1 No resource constraint
Design (tasks)	3.31% (1067.2)	-0.06% (1032.4)
Construction (tasks)	5.3% (1042.45)	3.44% (1024.05)
Operation (tasks)	-0.1% (1027.46)	-0.1% (1027.3)
Total (tasks)	2.8% (3137.11)	1.06% (3083.86)

The results support the emphasis placed on alignment by UK reports (Latham, 1994; Egan, 1998). The results echo the trade-off faced by the sustainability team leader in the building case, who commented that the time and human resources required for a complete energy modelling study was just not enough and would probably make a positive difference in building performance. The results illustrate the synergy of partner alignment and resource availability and raise the issue of how to achieve this in practice through appropriate contracts that incentivize CSC partners.

4.4 The Effect of Early Partner Engagement on Performance

The DEC A goal increased project complexity relative to the norm for office buildings. One way to cope with complexity and improve project performance is to develop early partner alignment on building performance targets (Hong *et al.*, 2004; Chua and Aslam Hossain, 2011). An early partner engagement scenario is simulated where partner interaction begins at the start of the simulation and is independent from project work timeline (Appendix C). Simulation results show improved building performance (Figure 6, right), in agreement with research which shows that the lack of front-end development activities prior to project execution can lead to low building performance (Suprapto et al., 2015).

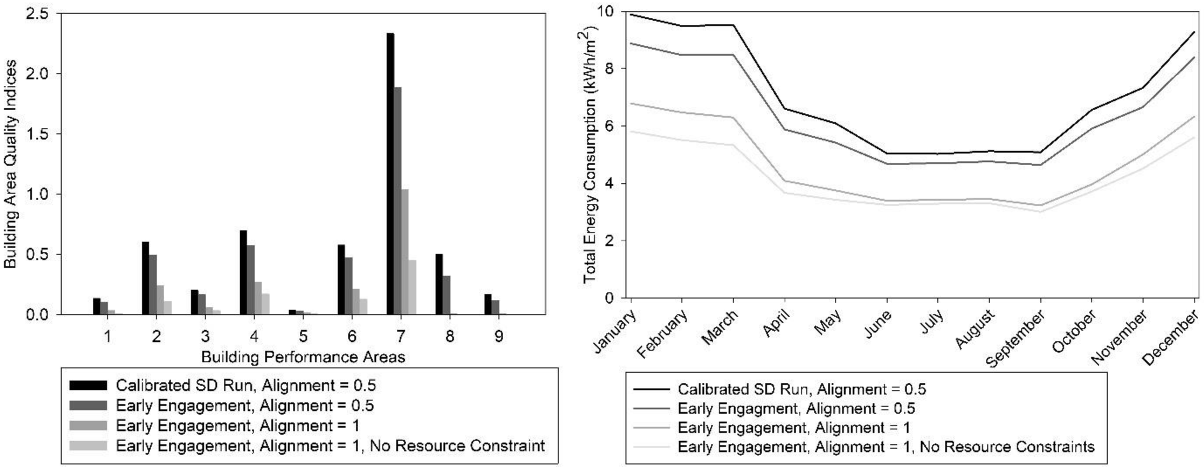


Figure 6 Effect of partner engagement and communication on building area quality (left), and building energy consumption (right).

Energy costs relative to the calibrated SD run decrease by 7.61% with early engagement, 32.7% with increased alignment, and 37.7% without resource constraints, with corresponding CO_2 emissions reductions (Table 4).

Table 4 Annual building energy cost and CO_2 emissions

Building Performance % Change to Calibrated SD run	Early engagement, Initial Alignment = 0.5	Early engagement, Initial Alignment = 1	Early engagement Initial Alignment = 1 No resource constraints
Total annual energy cost (£/m^2)	-7.61% (8.25)	-32.7% (6.01)	-37.7% (5.62)
Total annual CO_2 emissions (kg/m^2)	-8.08% (34.01)	-32.97% (24.80)	-37.92% (22.97)

Early engagement generates additional rework (Table 5) in the design stage (1.06%), but less in downstream stages. The engagement of different partners in different project stages creates an asymmetrical value appropriation barrier in situations where design stage partners may end up doing more work without necessarily reaping the benefits. The UK industry fragmentation compounds this asymmetry. The issue is whether this asymmetry can be overcome by appropriate incentives in procurement routes. An issue for further consideration is quality assurance in procurement routes such as Design and Build contracts, which are designed to facilitate partner engagement. The early engagement emphasis is good but it may also compromise on quality assurance in Design and Build contracts versus the traditional procurement route where there are fixed stage gates.

Table 5 The effect of early engagement, alignment and resource constraints on work done across stages relative to reference run

Project Work % Change to Reference SD Run	Early engagement Alignment = 0.5	Early engagement Alignment = 1	Early engagement Alignment = 1 No resource constraints
Design (tasks)	1.06% (1044.06)	8.0% (1115.67)	0.96% (1042.96)
Construction (tasks)	-0.05% (989.45)	12.6% (1114.74)	4.78% (1037.28)
Operation (tasks)	-1.27% (1015.43)	-0.75% (1020.78)	-0.4% (1024.27)

Total (tasks)	-0.08% (3048.95)	6.5% (3251.19)	2.74% (3104.51)

4.5 The Effect of Energy Testing on Performance

The results in sections 4.3-4.4 show that rework increases with alignment at the design and construction stages, something which may be avoided through higher testing thoroughness H_i. Testing in design stage involves BPM, but it is not integrated into design decision-making and is often executed at the end of the stage (Schlueter and Thesseling, 2009). The energy budget for the building was derived through energy calculations in the design stage. It was based on quasi steady-state method rather than more advanced modelling using dynamic simulation with hourly resolution, while energy performance was a client priority. The sustainability team leader estimated that a complete energy modelling study required more than a week, *"…it would be a lot more than that, once you actually went through all the sensitivities…".* Moreover, it could raise liability issues with other project partners or the client. Such liabilities are a barrier to the effective application of energy modelling in building projects (Oliveira *et al.*, 2017).

The energy testing scenario explores the effect of better energy modelling testing on building performance. The thoroughness H_i for design stage testing is varied for the three building areas that energy test can affect. Results show that improved testing can reduce energy costs by 8.42% and CO_2 emissions by 35% (Table 6). Improved testing requires 1.2% of additional work at the design stage (Table 7), and significantly less work in construction stage compared to scenarios in sections 4.3-4.4.

Table 6 The effect of energy modelling testing in design stage on building energy performance[12]

	Testing Thoroughness %			
Building performance % change to 40% run	40	60	80	100
Total annual energy cost (£/m^2)	(8.93)	-8.66% (3.02)	-8.42% (5.71)	-8.42% (5.71)
Total annual CO_2 emissions (kg/m^2)	(37.00)	35.94% (2.86)	34.99% (5.43)	34.99% (5.43)

[12] Varying the testing values in the SD model from 80 to 100% does not produce significant performance changes in the BPM model.

Table 7 The effect of energy modelling testing in design stage, on work variation across stages

	Testing Thoroughness %			
Project Work % change to 40% run	40	60	80	100
Design (tasks)	 (1031.55)	0.6% (1037.76)	1.2% (1043.95)	1.77% (1049.83)
Construction (tasks)	 (990.70)	-0.2% (988.65)	-0.4% (986.78)	-0.56% (985.14)
Operation (tasks)	 (1028.44)	0.00% (1028.47)	0.00% (1028.5)	0.00% (1028.53)
Total (tasks)	 (3050.69)	0.14% (3054.88)	0.28% (3059.23)	0.42% (3063.49)

The requirement for additional resources to do the testing can be overcome with better partner alignment between design and construction stages. This is because the building energy budget was determined at the design stage and later revisited by partners at the construction stage. increased alignment in this case would permit joint consideration of energy budget calculations. Such an opportunity exists in most building projects and additional consultancy fees are not required as from a client point of view energy modelling and testing has already been paid for as it is required under current UK regulations. The pooling of resources would in part overcome resource restrictions. However, there is the issue of overcoming the value appropriation asymmetry in the CSC.

4.6 The Effect of Soft Landings Approach on Performance

The case building was the first in the UK to follow a four year Soft Landings approach to engage designers and constructors beyond building commission to improve building energy performance (De Wilde, 2014). Building monitoring data demonstrate operational performance improvements that brought building performance close to DEC A rating. Nevertheless, an interview with an independent commission manager indicated that project partners try to avoid additional work after commissioning, so some documented problems remain unresolved. The resulting question is whether more testing, or early partner engagement will improve operational building performance or even substitute the Soft Landings approach?

This scenario is tested by removing defect rework at the operation stage and raising design stage energy testing to 100%. The results show that energy costs increase by 10.08% without Soft

Landings (Table 8). Early partner engagement could compensate partly for this and more thorough testing would reduce energy costs by 10.53% with corresponding CO_2 emission reduction (Table 9). These results support the Soft Landings approach implemented currently in the UK (De Wilde, 2014). It is likely better to have it than not have it in current procurement routes.

Table 8 Total annual energy cost results testing for Soft Landings, and early engagement

Cost % change to calibrated run	With Soft Landings	Without Soft Landings	Without Soft Landings Early engagement
Calibrated run		10.08%	2.8%
(£/m^2)	(8.93)	(9.83)	(9.18)
100% testing	-5.71%	7.73%	-10.53%
(£/m^2)	(8.42)	(9.62)	(7.99)

Table 9 Total annual CO_2 emissions results testing for Soft Landings, and early engagement relative to calibrated run

CO_2 emissions % change to calibrated run	With Soft Landings	Without Soft Landings	Without Soft Landings Early engagement
Calibrated run		9.84%	2.43%
(kg/m^2)	(37.00)	(40.64)	(37.9)
100% testing	-5.43%	9.29%	-10.0%
(kg/m^2)	(34.99)	(38.24)	(33.28)

The removal of Soft Landings in the calibrated run generates 5.66% less work and the early engagement figure is similar (Table 10). The variation of work along the three stages is also similar in both scenarios. Project work without Soft Landings is less but it also generates worse building performance (Table 8). The 100% energy testing scenario generates a similar reduction in total work but it improves building performance.

Table 10 The effect of Soft Landings, early engagement and energy testing on work variation across stages relative to calibrated run

	Project Work % Change to calibrated run	With Soft Landings	Without Soft Landings	Without Soft Landings Early engagement
Calibrated Run	Design		0.07	0.9
	(tasks)	(1033.05)	(1032.26)	(1042.41)
	Construction		-4.4	-4.67
	(tasks)	(989.95)	(946.49)	(943.71)

	Operation (tasks)	 (1028.45)	-12.49 (899.97)	-12.49 (899.97)
	Total (tasks)	 (3051.45)	-5.66 (2878.72)	-5.42 (2886.09)
100% Testing	Design (tasks)	1.62 (1049.83)	1.55 (1049.04)	0.88 (1059.06)
	Construction (tasks)	-0.49 (985.14)	-4.39 (946.5)	-4.2 (943.72)
	Operation (tasks)	0.0 (1028.53)	-12.49 (899.97)	-12.49 (899.97)
	Total (tasks)	0.4 (3063.49)	-5.11 (2895.51)	-5.25 (2902.74)

The results indicate that it is not easy to substitute the Soft Landings approach with early engagement and improvements in the design stage. Such improvements may compensate part or all of the performance lost with no Soft Landings but they require considerably more thorough work, time and cost for the client, in return for reduced work in construction and operation stages. This is likely a non-feasible option due to asymmetry in value appropriation for CSC partners in current procurement routes.

Moreover, there is a positive perception of Soft Landings in the UK industry and post completion improvements are seen as cost effective. Obviously, better decisions at the design stage would pay off, but that is not the spirit of Soft Landings as it encompasses the entire project duration and at each stage focuses on tangible outcomes for operational performance. Soft Landings does not shift attention from critical design activities to post commission activities. This is because it involves critical design decisions at the design stage to set key performance indicators and allocate resources.

Rather than consider substitutes to Soft Landings a more appropriate approach would be that of judicious application adapted to the building context. In the case building of this paper, the landlord (client) intended to occupy the building for a long time so there was a clear incentive for Soft Landings. However, this is not the case in speculative development scenarios and perhaps this is where a greater early emphasis would be warranted.

5 Discussion

5.1 Theoretical and Methodological Contribution

The theoretical contribution of the paper is the integration and operationalization of project partner alignment and information flows in the core SD project management model (Ford and Sterman, 1998). This facilitates the exploration of industry fragmentation and CSC collaboration dynamics, and their influence on operational building performance and CO_2 emissions, a topical issue in lieu of climate change, that is neglected in SD project management literature. The modelling framework is a first step to explore such effects in more cases and produce generalizable results.

The methodological contribution is the novel integration of the generic SD project management model to a BPM. In doing so, the multi-methodology framework has simultaneously theoretical generality and situational grounding, while being methodologically rigorous and practically relevant to both academic fields (Ketokivi and Choi, 2014). The intended aim is to produce research to systematically develop management lessons from project to project and inform the way industry insiders perceive CSC collaboration so that they consider seriously mechanisms for sufficient, timely and accurate information exchange for CSC governance and operational building performance.

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. It is possible, in principle, to apply the same modelling framework in other types buildings provided that there is an energy performance related clause in the development contract in place with the client. The framework can function as a post-project review tool or generic learning tool and facilitate strategic learning for those involved in such projects as it is done often with classical SD project management models (Lyneis and Ford, 2007). In this capacity, it can also function as an education and training tool for practitioners and academics alike.

The application of the framework is not limited by the type of buildings. It is data availability on case specific data that may impact its successful application. For example, limited data availability on, and access to key project stakeholders may compromise the assessment of project partner alignment and communication flows, partner interactions across stages, and possible adjustments necessary to the SD component for a specific building case. Similarly, the identification and validation of the root causes of performance gap, and building defect areas, is based on analysis on the initial, calibrated BPM. It is important to gain access to obtain onsite monitoring data on the building to increase confidence on estimation of building defect areas.

5.2 Practical Implications, Limitations and future work

The practical implications of this paper are towards meeting the 80% emission reduction target set by the UK government for 2050. This requires a focus on the construction project management process that delivers buildings and an in-depth analysis of its implications for operational building performance. The approach in the paper is particularly relevant in building contracts with energy performance targets, a rising trend in the UK and globally (Sorrell, 2007; Nolden and Sorrell, 2016).

The managerial implications of the simulation results are in line with conventional wisdom on project performance in terms of cost, time, and quality. An early focus on building performance targets and testing can boost CSC alignment, information availability, and enable the achievement of performance targets. Project performance targets increase project complexity, and information sharing becomes an important enabler of coordinated responses to unanticipated events that decrease operational building performance, a common occurrence in projects. Conventional project management performance metrics and tools ignore some of the behavioural and feedback mechanisms in such contexts and confound potentially useful project related learning (Browning, 2010). Learning from projects needs a more sophisticated approach than simply documenting lessons (Williams, 2003). The application of SD can facilitate project related learning which is inhibited by delays that increase the complexity and ambiguity between action and payoffs (Cooper *et al.*, 2002; Rahmandad, 2008).

The study has some data and methodological limitations, and some potential for future development work. The case building had no explicit IEQ target set, so it is not possible to explore the implications of the energy performance versus IEQ performance trade off. The building was commissioned before the start of the research project. This limited access to some project partners that were already involved in new projects. It also limited data availability on total resources per stage (due its multi organizational nature), and partner resource prioritization and allocation over other projects. Expert judgement was used to calibrate s-curves for each stage and account partially for these limitations.

The real building performance is known in detail through in-situ monitoring and BPM, so it is possible to claim that resource related quality effects have been captured implicitly in expert estimates on quality, testing thoroughness, and resource availability. Accurate resource availability information would increase the realism of the retrospective analysis and enable a better assessment of information exchange and collaboration effects on building quality.

One way to overcome such limitations in future research is to follow a building project from its inception to its completion through a process tracing research design (Collier, 2011; Bennett and Checkel, 2014). This would reduce the reliance on interviews, and post hoc estimates, and it would increase managerial relevance as it would consider explicitly managerial perspectives at the outset of the research project (Holmstrom *et al.*, 2009). Tracing a building project in real time, would enable the research team to develop a nuanced sense of the framework application context better than any ex post study could.

A closer look on particular projects would improve the future application of the framework in five ways. First, it would inform SD model development and enable the introduction of partially defective tasks that are still good enough to go through quality assurance. The quality threshold related to specific building areas that can be tolerated is project specific, and closer engagement with a project would enable the research team to account for this and explore the balance between alignment and quality assurance at each stage in a more fine-grained way. This raises the issue of early project partner engagement versus having project quality stage gates in the UK. A range of procurement routes have been developed that reflect different rationales around this trade off. For example, the design and build procurement route provides a better opportunity for CSC integration at the expense of quality checkpoints.

Second, it would expand the scope of the framework from quality to time and cost and facilitate the exploration of CSC partner relationships effect on these aspects. For example, it has been shown that cost performance has a more significant association to CSC relations (Meng, 2012). Future model development should account explicitly for value engineering and the 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.

Third, it would facilitate the analysis of communication attributes and a more detailed analysis of intra- and inter-stage interactions. This would ground the assumptions on partner alignment and their aggregation in CSC stages on data. Future model development could elaborate on the effect of alignment and information sharing on project quality based on project novelty, size, complexity and difficulty (Yan and Dooley, 2013; Zhu and Mostafavi, 2017), rather than rely on estimates for the contribution of each stage to building quality and the testing thoroughness level.

Fourth, it would provide an opportunity to appreciate sources of project uncertainty e.g. lack of information, ambiguity, project partners characteristics, trade-offs between trust and control mechanisms, and partner agendas in the project life cycle (Atkinson *et al.*, 2006). Project uncertainty can have a fundamental effect on project performance and its explicit consideration would enable a better appreciation of the role of alignment on project delivery.

Fifth, framework development could be geared to improve practices in the UK building industry and cater to manager needs. The worse-before-better trade-offs involved in upfront, organizational capability investments in quality, and cost make it harder to learn and pursue the more flexible learning focused style of project management (Repenning and Sterman, 2002; Williams, 2008). The delays involved in firm strategies to deliver high performance buildings, lead to myopic attitude towards the intermediate steps that are required to increase performance. Furthermore, it is difficult to transfer lessons within an organization as there is lack of time, management support, and incentive to do so (Williams, 2008). The gamification of the framework in this paper can be used as the basis for decision support, for example like the classic beer game and other management simulators (Morecroft and Sterman, 1994; Sterman, 2000).

6 Conclusion and Policy Implications

The paper develops an SD project management model and integrates it to a building performance model to enable the in-depth exploration the effect of CSC partner alignment, coordination and information sharing on actual building operational performance levels and CO_2 emissions. It is the first attempt to bridge two simulation methods from two disciplines: project management and building science, in a multi methodology framework. In the building case explored in the paper project partners were aligned and coordinated to deliver a high-quality building because of its potentially significant reputational effects. Simulation results show how alignment can influence task performance, and operational building performance, energy consumption, and CO_2 emissions. Depending on partner alignment and project resource constraints, reductions in total annual energy costs and total annual CO_2 emissions could reach approximately 12%, while with early project partner engagement the figure could rise up to 37%. Thus. in terms of the question set in the introduction, further building performance improvements would have been possible in this case, even though building performance is already high. By extension better performance should be possible in other cases too.

The results provide also support for the application of Soft Landings approach in the UK industry. The research design in this paper could be applied to other UK building projects and include polar opposite cases with no explicit energy goals to explore the benefits of the application of the Soft Landings approach or alternative ways to deliver similar building performance. Such research would provide supportive evidence for the contribution of Soft Landings approach which currently constitutes a best practice guideline rather than compulsory practice in the UK. However, building performance improvements cannot depend only on voluntary approaches. Organizations might have additional procedures in place that they don't always follow if they don't perceive immediate market benefits, or if there is asymmetrical value appropriation. The delivery of building performance requires partners to think and act strategically to overcome industry fragmentation impediments and resource constraints.

The delivery of high building performance needs to be strengthened through suitable policies and incentives to improve partner alignment. One of the key messages of this paper is that the design and build procurement route along with a Soft Landings approach is beneficial for building performance. The DEC and Soft Landings schemes are a good starting point but they need a less complex, policy landscape to enable alignment of project partners around meaningful metrics of building operational performance. UK policy should focus more on actual energy use than theoretical estimates, and the behavioural drivers for improvement that are at least as important as financial ones . UK policy focus on theoretical energy use estimates should be complemented with a focus on actual energy use and behavioural drivers for CSC improvements .

In conclusion, this research makes clear that it is necessary to increase partner alignment around building performance criteria to improve building performance and meet emission reduction targets. Policy and project governance interventions and procurement contracts can help overcome the short-run incentives that produce moderate results and produce win-win outcomes for industry actors and clients alike . Policies to increase operational performance transparency are important for building energy management and well-focused investment in energy saving measures, probably more so than a compelling financial case. Transparency is an essential foundation for accountability and reputational pressure, a convergence point for a whole range of initiatives by all industry actors, and a mechanism to provide feedback on which interventions work well and which do not .

Appendix A Interviewee Profiles

Profile	Organizational Post	Experience at current post	Total Experience	Project relevance
1	Building energy manager	7 years	31 years	Facility manager for the client
2	Corporate Sustainability Officer Strategy & Performance	4 years	8 years	Manager in client organization
3	Director for sustainable architecture & research	2 years	13 years	Architect in design firm
4	Principal Energy Solutions Engineer	8 years	20 years	Main contractor firm
5	Sustainability team leader	18 years	18 years	Concept MEP design firm
6	Environmental team leader	4 years	14 years	Industry expert
7	Senior Sustainability Manager	9 years	17 years	Industry expert

Appendix B Model Parameter Values and Calibration

Model setup: A_i^o Values

The variables setting the initial levels of alignment are *Initial Level of Inter Stage Alignment* and *Initial Level of Intra Stage Alignment*. These are set to a value of 0.5 based on interviews but also on consideration of what the extremes of 0 and 1 represent in reality. 0 represents a state of total fragmentation in the construction chain where project partners are willing only to do the bare minimum to deliver the project. Clearly this is not representative of the conditions of the case project building. The importance of the project to all the involved project partners was established through the interviews and the workshop. 1 represents a state of alignment with a minimum fragmentation. In effect the project partners operate in a single organization from project start to finish. They share the same organizational routines and procedures and as such there is a common perception of problem solving related knowledge. This is also not representative of the conditions of the case project building. Project partners organizations had previously collaborated in different projects. Nevertheless, as is common practice in project based organizations, the make up of teams assigned to projects is varied both to diffuse knowledge in organizations, due to turnover, and seniority. Thus, the alignment values chosen for the initial level variables was 0.5. This was varied to explore the effect of alignment on building project quality. Results are presented and discussed in the paper.

Logistic Curve Calibration

The general form of the logistic curve is given by

$$Y_t = A + \frac{K - A}{(1 + Qe^{-B(t-M)})^{1/v}}$$

Where K is the upper asymptote, A is the lower asymptote, v affects near which asymptote maximum growth occurs, M is the starting time, B is the growth rate. The values given to B: {1, 1.2, 1.4} based on expert estimates on the shape of the curves. The rest of the variables were given the following values: Q = 100, N=1, K=1, A=0, M=0 for all three curves. Each curve is shifted in time so that it starts at the project stage start (Figure 7).

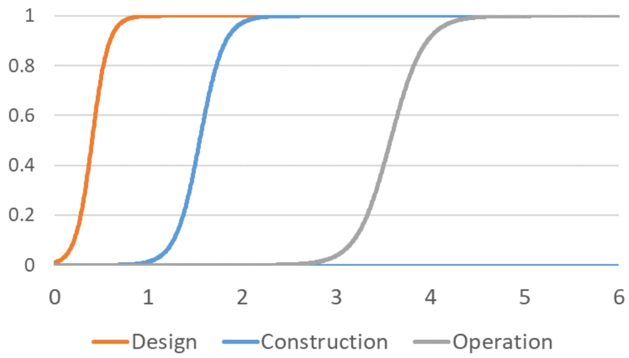


Figure 7 S-curves implemented in SD model

Knock-on effects between stages

The effect of defects in upstream project stages on quality of work in downstream stages is important in construction projects. In order to account for this effect between design and build stages and between build and operation stages two variables are used: *Strength of Defect Effect Design Stage* and *Strength of Defect Effect Build Stage*. They represent the effect of defects in a stage on downstream work. They are modelled with an 9-element array to account for the 9 performance areas in the case building project. These two variables are used to further calibrate the SD model using the powersim solver. The objective is to minimize the error between the model output from the *Absolute Deviation per Defect Type* variable and the actual performance gap documented in Jain et al. (2017).

Calibration Optimization set up

To calibrate the SD model, it is assumed that knock-on defect effects between stages have a greater than unit effect, in line with theory (Lyneis and Ford, 2007) and industry evidence (Parvan *et al.*, 2015). The defect knock-on effect N_{ij} from stage *i* to *j* per building area depends on the sum of undiscovered defects T_{ui}, the known defects T_{Fi} normalized against initial design scope T_{total}, and the knock-on effect strength γ. The model was calibrated by optimization of γ values to minimize simultaneously SD output error to performance gap figures for each building area (see Appendix B). N_{ij} is given by:

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

The optimization was carried out with powersim evolutionary based search algorithm with the following settings: generations 300, 20 parents, 100 offsprings, minimum convergence 0.001, seed 100. The average of the best estimates of building performance experts are used as inputs for the following variables:

Defect Testing Thoroughness Design Stage, Defect Testing Thoroughness Build Stage, Defect Testing Thoroughness Operation Stage, Contribution of Intra Stage Defect Design Stage, Contribution of Intra Stage Defect Build Stage, Contribution of Intra Stage Defect Operation Stage

The optimization algorithm is set with two variables as the decision variables: *Strength of Defect Effect Design Stage* and *Strength of Defect Effect Build Stage*. Their value range was {2..22}.

Optimization output

The output values of the optimization for *Strength of Defect Effect Design Stage* are:
{4.860322026972, 5.147380257948, 11.84143855979, 5.806271150768, 14.13033355421, 4.331329524249, 3.826097102329, 7.940018070697, 8.661140334086}

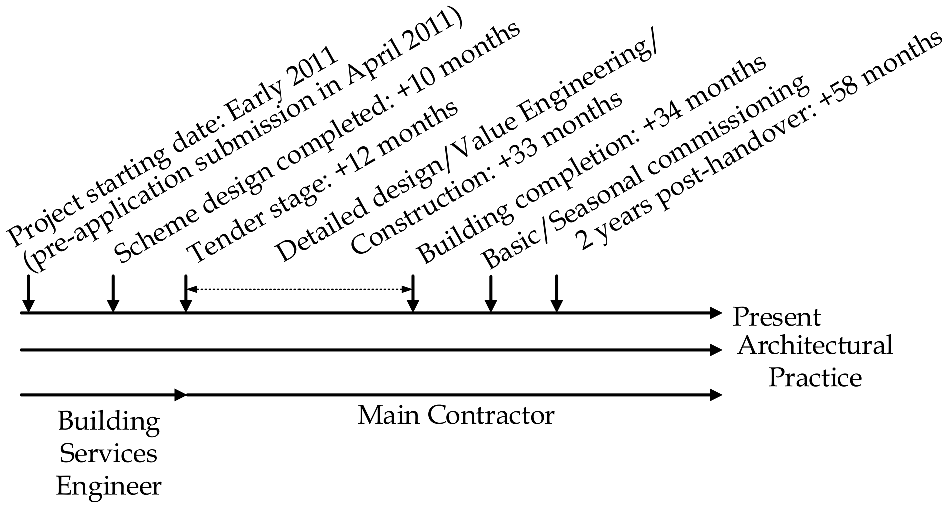
The output values of the optimization for *Strength of Defect Effect Build Stage* are:
{7.896188103852, 3.061016094028, 3.693329358534, 2.701588046766, 9.49887414906, 4.481926965231, 0.7682376362055, 10.83069386779, 7.941872606196}

These values give the following array values for the *Absolute Deviation per Defect Type* with a timestep of 0.125 months and simulation time of 5 years with Euler integration, and a bank calendar setting:
{0.03540714725446, 0.00008080493773643, 0.04940963516647, 0.00001158285674785, 0.01991431077897, 0.00006305162672193, 0.0003270901380148, 0.000103254610913, 0.1696656846044}

The average error is 0.2749825619745.

Appendix C Project Timeline

Considerable time was spent in preplanning and approval according to the client. The project duration from start to finish was approximately 2.5 years. Figure 1 illustrates some of the main milestones of the project. The project started with pre-application submission. The scheme design was completed 10 months later and then the project entered the tender stage. The detailed design, value engineering and actual construction of the building were all concurrent activities with considerable overlap until the final completion of the building 33 months later. The finished building went through basic/seasonal commissioning, for two years and the two-year post commission period has been already completed as of January 2017.



Appendix D Case estimates

Table 11 Expert 1 stage contribution P_i to end building quality estimates: minimum, best, maximum

	Conceptual Design			Detailed Design & Build			Operation		
Issues	Min	Best	Max	Min	Best	Max	Min	Best	Max
Heating System Efficiency	30%	40%	50%	30%	40%	50%	10%	20%	30%
Lighting energy use	30%	40%	50%	30%	40%	50%	10%	20%	30%
Office equipment power density	20%	25%	30%	20%	25%	30%	40%	50%	60%
Occupant density	20%	25%	30%	20%	25%	30%	40%	50%	60%
Heating Set point	40%	50%	60%	0%	0%	0%	40%	50%	60%
Occupancy hours	20%	25%	30%	20%	25%	30%	40%	50%	60%
Infiltration[13]									
Ventilation	10%	20%	30%	30%	40%	50%	30%	40%	50%
Operation Schedule (Pumps/Vents)	0%	0%	0%	5%	10%	15%	85%	90%	95%

Table 12 Expert 2 testing thoroughness H_i estimates: minimum, best, maximum

	Conceptual Design			Detailed Design & Build			Operation		
Issues	Min	Best	Max	Min	Best	Max	Min	Best	Max
Heating System Efficiency	40%	50%	60%	20%	30%	40%	70%	80%	90%
Lighting energy use	20%	30%	40%	20%	30%	40%	70%	80%	90%
Office equipment power density	40%	50%	60%	0%	0%	0%	40%	50%	60%
Occupant density	40%	50%	60%	0%	0%	0%	40%	50%	60%
Heating Set point	40%	50%	60%	0%	0%	0%	40%	50%	60%
Occupancy hours	40%	50%	60%	0%	0%	0%	40%	50%	60%
Infiltration[14]									
Ventilation	40%	50%	60%	20%	30%	40%	40%	50%	60%
Operation Schedule (Pumps/Vents)	0%	0%	0%	0%	0%	0%	100%	100 %	100 %

[13] The expert did not provide an estimate for infiltration because he did not have access to the calibrated model for the case building.
[14] The expert did not provide an estimate for infiltration because he did not have access to the calibrated model for the case building.

Table 13 Expert 2 stage contribution P_i to end building quality estimates: minimum, best, maximum

	Conceptual Design			Detailed Design & Build			Operation		
	Min	Best	Max	Min	Best	Max	Min	Best	Max
Heating System Efficiency	20%	30%	35%	25%	30%	40%	30%	40%	50%
Lighting power density	45%	50%	55%	0%	0%	0%	45%	50%	65%
Office equipment power density	45%	50%	55%	0%	0%	0%	45%	50%	65%
Occupant density	45%	50%	65%	0%	0%	0%	45%	50%	55%
Heating Set point	45%	50%	55%	0%	0%	0%	45%	50%	65%
Occupancy hours	45%	50%	65%	0%	0%	0%	45%	50%	55%
Infiltration	40%	40%	60%	40%	40%	60%	10%	20%	20%
Ventilation	5%	10%	15%	15%	20%	25%	60%	70%	90%
Operation Schedule (Pumps/Vents)	0%	0%	0%	5%	10%	15%	85%	90%	95%

Table 14 Expert 2 testing thoroughness H_i estimates: minimum, best, maximum

	Conceptual Design			Detailed Design & Build			Operation		
	Min	Best	Max	Min	Best	Max	Min	Best	Max
Heating System Efficiency	30%	45%	60%	10%	25%	40%	20%	25%	30%
Lighting power density	50%	60%	70%	0%	0%	0%	10%	25%	40%
Office equipment power density	30%	50%	70%	0%	0%	0%	10%	25%	40%
Occupant density	20%	35%	50%	0%	0%	0%	0%	0%	0%
Heating Set point	20%	40%	60%	0%	0%	0%	20%	40%	60%
Occupancy hours	20%	35%	50%	0%	0%	0%	0%	0%	0%
Infiltration	30%	45%	60%	30%	40%	50%	10%	25%	40%
Ventilation	40%	55%	70%	40%	55%	70%	10%	25%	40%
Operation Schedule (Pumps/Vents)	0%	0%	0%	0%	0%	0%	100%	100%	100%

Appendix E Model Equations

Task flow structure

Initial Completion Rate Design Stage

min('Tasks Not Completed Design Stage'/'Avg Initial Completion Duration Design Stage', 'Actor Work Capacity'[1], 'Tasks Available for Completion Design Stage'/'Avg Initial Completion Duration Design Stage')

Logic: Project work is completed subject to capacity constraints. This is provided that there are tasks available for completion. This logic applies also to *Initial Completion Rate Build Stage* and *Initial Completion Rate Operation Stage*.

Discover Intra Stage Defects Design Stage

min('Quality Assurance Design Stage','Tasks Completed Not Checked Design Stage' *'Probability of Intra Defect Discovery Design Stage'*'Probability of Intra Stage Defect Design Stage')/1<<mo>>)

Logic: The rate of discovering intra stage defects is the min of quality assurance capacity, or the available tasks completed times the probability of discovering defects when there is a defect in the stage. This is influenced by product of the probability of defect discovery and the probability of generating a defect in the stage in the first place. This logic applies also to *Initial Completion Rate Build Stage* and *Initial Completion Rate Operation Stage*.

Discover Intra Stage Defects Build Stage

min('Quality Assurance Build Stage','Tasks Completed not Checked Build Stage'/1<<mo>>
'Probability of Intra Defect Discovery Build Stage''Probability Intra Stage Defect Build Stage')
+('Tasks Completed not Checked Build Stage'*'Proportion of Design Defects Possible to Rework in Build Stage'
*'Probability of Defects Design to Build Stage' *'Probability of Intra Defect Discovery Build Stage'/1<<mo>>)

Logic: The rate of discovering intra stage defects is the min of quality assurance capacity, or the available tasks completed times the probability of discovering defects when there is a defect in the stage. The difference to design stage is that there is a proportion of design defects that is not possible to rework in the build stage. This is what the plus term accounts for. This logic is the same for *Discover Intra Stage Defects Operation Stage*.

Change Task Rate Design Stage

min('Actor Work Capacity'[1]-'Initial Completion Rate Design Stage' , 'Tasks to be Iterated Design Stage'/'Avg Iteration Duration Design Stage')

Logic: Work on new tasks gets precedence over rework. Rework is done only if there is surplus of capacity. The same logic applies to *Change Task Rate Build Stage* and *Change Task Rate Commission Stage*.

Quality Assurance Design Stage

max(0/1<<mo>>,'Actor Work Capacity'[1]-'Initial Completion Rate Design Stage')

Logic: Quality assurance is used for testing tasks. It is assumed that total actor capacity can be allocated to task completion or testing of competed tasks. It is equal to total capacity- capacity used to complete tasks. The same logic applies to *Quality Assurance Build Stage* and *Quality Assurance Commission Stage*.

Discover Inter Stage Defects Build Stage

min('Tasks Completed not Checked Build Stage'/1<<mo>>,'Quality Assurance Build Stage' *max(0,('Probability of Generating Inter Stage Defect in Design Stage'-'Probability Intra Stage Defect Build Stage')))*(1-'Proportion of Design Defects Possible to Rework in Build Stage')

Logic: It is assumed that developers will correct defects generated within their own phase before bringing those tasks to coordination so as to avoid revealing to colleagues that they have made errors. This is based on the assumption that they are not willing to accept work of a lower quality level than what they are willing to deliver. That is *if* 'Probability of Inter Stage Defect in Design Stage' <'Probability Intra Stage Defect Build Stage' *then* all defects are kept in the stage. The rate at which this is done is subject to quality assurance capacity constraints. Here priority is on quality assurance for intra stage task testing. The same logic applies to *Discover Inter Stage Defects Commission Stage*.

Approve Tasks Rate Design Stage

min('Tasks Completed Not Checked Design Stage'/1<<mo>>, 'Quality Assurance Design Stage'-'Discover Intra Stage Defects Design Stage'))

+'Defect Correction Rate Design Stage'

Logic: The tasks that are approved are the minimum of those completed and checked in quality assurance and no defects were found times the probability of not finding defects.. the plus term is there to account for the extreme that all tasks are defective and the approval rate then is the correction rate.

Release Task Rate Design Stage

'Tasks Approved Design Stage'*'Release Time Design Stage'/'Release Task Delay Design Stage'

Logic: the logic is that tasks are released to subsequent stages at an appropriate release time. The same logic applies to *Release Task Rate Build Stage* and *Release Task Rate Operation Stage*.

Release Time Design Stage

If ('Release Package Size Design Stage'/('Scope Design Stage'-'Tasks Released Design Stage')
<='Tasks Approved Design Stage',1,0)

Logic: This functions like a switch. Tasks in project are released in packages e.g. in software projects. The *Release Package Size Design Stage* is a constant. The logic is that there must be enough tasks approved so that their number is higher than the first part of the if function. The same logic applies to *Release Time Build Stage* and *Release Time Commission Stage*.

Tasks Coordinate Design Stage Build Stage

min(1,'Actor Design-Build Alignment')*'Tasks to Coordinate Build Stage'/'Avg Coord Duration Build Stage'*(1-'Project Changes Difficulty'[1])

Logic: Alignment functions as a switch. With no alignment no tasks are returned to previous stages. Coordination takes place as long as the 'Project Changes Difficulty' remains less than one. This variable is implemented with a general logistic function. See calibration for details. The same logic applies to *Tasks Coordinate Build Stage Commission Stage* and *Coordinate Operation Post Commision*.

Tasks Not Coordinated Design Build Stage

(1-min(1,'Actor Design-Build Alignment'))*'Tasks to Coordinate Build Stage'/'Avg Coord Duration Build Stage'

Logic: This is the complementary variable to *Tasks Coordinate Design Stage Build Stage*. Alignment functions as a switch. With no alignment between CSC partners all tasks send downstream. The same logic applies to *Tasks Not Coordinated Build Operation Stage*.

Fraction Perceived Satisfactory Design Stage

'Net Work Done Design Stage'/'Scope Design Stage'

Logic: the stock of net work done is tasks send to build stage minus returns of defects. The same logic applies to *Fraction Perceived Satisfactory Build Stage* and *Fraction Perceived Satisfactory Operation Stage*.

% Avail Internal Concurrence Design Stage

For (i=NofTasks|Graph('Fraction Perceived Satisfactory Design Stage'[i],0,1,
'Internal Process Concurrence Relation Graph Input Design Stage'[i]))

Logic: This is taken directly from Ford and Sterman 1998. The internal process concurrence relation capture the degree of sequentiality or concurrence of the tasks aggregated together within a phase, including possible changes in the degree of concurrence as the work progresses. The same logic applies to *% Avail Internal Concurrence Build Stage* and *% Avail Internal Concurrence Operation Stage*.

Tasks Available for Completion Design Stage

'Scope Design Stage'*min('% Avail Internal Concurrence Design Stage','% Available External Concurrence Design Stage')

Logic: The tasks available depends on whether additional intra stage work is required to proceed or more upstream tasks have to be delivered first. the same logic applies in *Tasks Available for Completion Build Stage* and *Tasks Available for Completion Operation Stage*.

% Available External Concurrence Design Stage

For (i=NofTasks|Graph('Fraction of Tasks Released from Design Stage'[i],0,1,'External Process Concurrence Relation Design Stage'[i]))

Logic: This is from Ford and Sterman (1998), meant to capture the work overlap relation between project phases. The same logic applies to *% Avail External Concurrence Build Stage* and *% Avail External Concurrence Operation Stage*.

Fraction of Tasks Released from Design Stage
'Tasks Not Completed Design Stage'/'Scope Design Stage'

Logic: the fraction is a function of the total work scope in design stage. The same logic applies in *Fraction of Tasks Released from Build Stage* and *Fraction of Tasks Released from Operation Stage*.

Defect flow structure

Generate Internal Defects in Completion Design Stage
'Initial Completion Rate Design Stage'*'Probability of Intra Stage Defect Design Stage'
*(1-'Actor Inter Stage Cumulative Communication'[1]/'Total Actor Tasks')

Logic: This is the internal defect generation rate for each stage. It is assumed that additional information processing between stages results in less defects being generated in a stage. the same logic applies to *Generate Internal Defects in Initial Completion Build Stage* and *Generate Internal Defects in Initial Completion Commission Stage*.

Defects Released Design Stage
max(0/1<<mo>>, min('Approve Tasks Rate Design Stage', 'Undiscovered Defects Design Stage'/1<<mo>>-'Discover Internal Defects Design Stage'))

Logic: The logic is that no defective tasks are released, if defective tasks discovered equal the number of undiscovered defects. The same logic applies to *Defects Released Build Stage* and *Approve Defects Operation Stage*.

Defects to Build Stage
'Defect Knock on Effect Design Stage' *('Defects Released Design Stage'+'Defects Released with Workarounds to Build Stage')

Logic: This flow is separate from *Defects Released Design Stage*. This enables to account for knock-on effects of defects in downstream stages using 'Defect Knock on Effect Design Stage'. The same logic applies to *Defects to Operation Stage*.

Defects Released with Workarounds to Build Stage
('Known Defects Design Stage'/1<<mo>>-'Defect Correction Rate Design Stage')
*'Project Changes Difficulty'[1]

Logic: This flow enables to account for defects that are treated with workarounds, when the difficulty in implementing changes to the project becomes greater. This is modelled in an s-curve. Defects with workarounds can have knock on effects on subsequent project stages. The same logic applies to *Defects Released with Workarounds to Build Stage*.

Defect Knock on Effect Design Stage
(1+('Undiscovered Defects Design Stage'+'Known Defects Design Stage')/'Scope Design Stage')^'Strength of Defect Effect Design Stage'

Logic: Undiscovered and known defects in a stage have knock on effects of greater magnitude in subsequent project stages. This magnitude is captured by *Strength of Defect Effect Design Stage.* The same logic applies to *Defect Knock on Effect Build Stage*.

Discover Internal Defects Design Stage
min('Undiscovered Defects Design Stage'/1<<mo>>,
'Discover Intra Stage Defects Design Stage')*'Probability of Intra Defect Discovery Design Stage'

Logic: This is the rate of discovering defects in each stage. Defects discovered in the stage are the minimum of the defects that exist or the probability of discovering defects in the stage. the same logic applies to *Discover Internal Defects Build Stage* and *Discover Internal Defects Operation Stage*.

Probability of Intra Defect Discovery Design Stage
min(1,'Initial Probability of Intra Defect Discovery Design Stage'
('Initial Probability of Intra Defect Discovery Design Stage'+'Switch Effect of Communication on Defect Detection'('Actor Inter Stage Cumulative Communication'[1]*'Actor Intra Stage Cumulative Communication'[1])/'Total Project Tasks Scope'^2)divz0('Initial Probability of Intra Defect Discovery Design Stage'))

Logic: The probability of discovering defects depends on cumulative inter and intra actor communication. The division with total actor tasks is made to keep probabilities between 0 and 1. It is assumed that a greater number of tasks requires a greater amount of information to ensure minimum defects occurring in any project stage. The same logic applies to *Probability of Intra Defect Discovery Build Stage* and *Probability of Intra Defect Discovery Operation Stage*.

Defect Correction Rate Design Stage
'Known Defects Design Stage' divz0 'Tasks to be Iterated Design Stage'
*(1-('Probability of Generating an Additional Internal Defect when Receiving Downstream Tasks Design Stage'))
'Change Task Rate Design Stage'(1-'Project Changes Difficulty'[1])

Logic: Defects are corrected as long as they are discovered, there are still tasks to be iterated, and the *Project Changes Difficulty* is less than 1. The correcting rate also depends on no additional defects being generated. The same logic applies to *Correcting Defects Build Stage* and *Correcting Defects Operation Stage*.

Generate Defects in Iteration Design Stage
'Known Defects Design Stage' divz0 'Tasks to be Iterated Design Stage'
*'Probability of Generating an Internal Defect in Iteration Design Stage'
*'Change Task Rate Design Stage'

Logic: The rate of defect generation in iteration, when trying to fix discovered defects. The divz0 is used as there are no *Tasks to be Iterated Design Stage* the defect generation rate must be zero. The same logic applies to *Generate Defects in Iteration Build Stage* and *Generate Defects in Iteration Operation Stage*.

Probability of Generating an Internal Defect in Iteration Design Stage
max(0,'Initial Probability of Generating an Internal Defect in Iteration Design Stage'
-('Actor Intra Stage Cumulative Communication'[1]
+'Actor Inter Stage Cumulative Communication'[1])
/'Total Actor Tasks')

Logic: That additional intra and inter stage information should decrease errors in iteration in the design stage. the same logic applies to *Probability of Generating an Internal Defect in Iteration Build Stage* and *Probability of Generating an Internal Defect in Iteration Operation Stage*.

Probability of Generating Additional Internal Defect when Receiving Downstream Tasks Design Stage
max(0,'Initial Probability of Generating an Additional Internal Defect when Receiving Downstream Tasks Design Stage'
-'Actor Inter Stage Cumulative Communication'[1]/'Total Actor Tasks')

Logic: The probability of correcting known defects is one unless additional defects are generated. The logic is that the greater the number of total actor tasks, the greater the amount of information exchange required to have an impact on this probability. The same logic applies to *Probability of Generating Additional Internal Defect when Receiving Downstream Tasks Build Stage* and *Probability of Generating Additional Internal Defect when Receiving Downstream Tasks Operation Stage*.

Discover Inter Stage Defects in Build Stage
min('Tasks Completed not Checked Build Stage'/1<<mo>>,
('Quality Assurance Build Stage'-'Discover IntraStage Defects Build Stage')
*max(0,('Probability of Defects Design to Build Stage'
-'Probability Intra Stage Defect Build Stage')*'Probability of Intra Defect Discovery Build Stage'))
*(1-'Proportion of Design Defects Possible to Rework in Build Stage')

Logic: This flow concerns the defects that are discovered in build stage but have not been generated or developed in these stages. This is the reason for the quality assurance – discover intra stage defects term. This term is multiplied by a probability term which is the probability of defects coming from design stage minus the intra stage defect probability times the probability of discovering this. This term is multiplied by the proportion of defects that must be sent back to design stage. The same logic applies to *Discover Inter Stage Defects in Operation Stage*.

<u>Return Defects to Design Stage</u>
'Discover Inter Stage Defects in Build Stage'/'Defect Knock on Effect Design Stage'

<u>Logic</u>: It is necessary to have a separate flow to return defects to the actual stock of known defects in design. This is because defect number in build stage is inflated. E.g. a design defect might generate 2 build defects, but if it is returned to design stages it must still be a single design defect. This is the reason to divide with Defect Knock on Effect Build Stage. the same logic applies to *Return Defects to Build Stage*.

Capacity Structure
<u>Capacity Increase</u>
'Additional Required Capacity'*For (i=NofActors|Step(1,StartTime+'Actor Entry Timing'[i]))
*min(1,'Relative Schedule Pressure')/'Work Capacity Adjustment Time'

<u>Logic</u>: Capacity is added at all cost to the project to finish in time and not reduce its scope if required time is less than available time then capacity should be added.

<u>Capacity Decrease</u>
max(0/1<<mo>>, 'Actor Work Capacity'-ArrSum('Net Project Remaining Work Per Stage')/1<<mo>>)/'Time to Reduce Work Capacity'

<u>Logic</u>: If available capacity is in excess of what is required to complete the remaining tasks then it is reduced. So when the project ends, capacity reduces to zero.

<u>Additional Required Capacity</u>
For (i=NofActors|ArrSum('Net Project Remaining Work Per Stage'[i]))
*{'Avg Initial Completion Duration Design Stage','Avg Initial Completion Duration Build Stage','Avg Initial Completion Duration Commission Stage'}
divz0('Individual Actor Available Time to Completion')/1<<mo>>

<u>Logic</u>: Calculates the required capacity per stage. The assumption is that all of the tasks need to be worked on in every stage.

<u>Net Project Remaining Work Per Stage</u>
{'Total Actor Tasks'-'Net Work Done Design Stage',
'Total Actor Tasks'-'Net Work Done Build Stage',
'Total Actor Tasks'-'Net Work Done Commission Stage'}

<u>Logic</u>: Calculates the remaining tasks for each stage. when they are zero then capacity should also go to zero. The assumption is that all of the tasks need to be worked on in every stage.

<u>Relative Schedule Pressure</u>
'Actor Schedule Pressure'divz0 'Initial Schedule Pressure'

<u>Logic</u>: It is assumed that an initial pressure to perform exists.

<u>Increase in Schedule Pressure</u>
(max(0,('Required Time to Completion'divz0'Individual Actor Available Time to Completion')
*('Sensitivity to Time Pressure')))/'Schedule Pressure Adjustment Delay'
*For(i=NofActors|Step(1,StartTime+'Actor Entry Timing'[i]))

<u>Logic</u>: As available time to completion decreases, pressure increases if there is a change in deadline then time to completion increases and momentarily pressure should not increase or even decrease.

<u>Decrease in Schedule Pressure</u>
max(0/1<<mo>>,'Actor Schedule Pressure'/('Actor Schedule Pressure Release Delay')
*For (I=1..3|(1-'Total Remaining Tasks'[i]/ArrSum('Total Actor Tasks'))))

Logic: The logic of the 1st line is it is harder to reduce pressure when there are a lot of remaining tasks. The logic of 3rd line is assuming that there is always less time to complete all the required tasks it is harder to reduce pressure if there are a lot of remaining tasks.

Total Remaining Tasks
{ArrSum('Remaining Tasks Design Stage'),ArrSum('Remaining Tasks Build Stage'),ArrSum('Remaining Tasks Commission Stage')}

Logic: It calculates the sum of remaining tasks per project stage.

Remaining Tasks Design Stage
'Total Actor Tasks'-'Net Work Done Design Stage'

Logic: It calculates the remaining tasks in a stage. the same logic applies to *Remaining Tasks Build Stage* and *Remaining Tasks Commission Stage*.

Required Time to Completion
max(0<<mo>>,{ArrSum('Remaining Tasks Design Stage')*'Avg Initial Completion Duration Design Stage'
,ArrSum('Remaining Tasks Build Stage')*'Avg Initial Completion Duration Build Stage'
,ArrSum('Remaining Tasks Commission Stage')*'Avg Initial Completion Duration Commission Stage'}divz0
Number(max('Additional Required Capacity', 'Actor Work Capacity')))

Logic: The required time to complete all tasks in a stage is number of tasks over time required to complete one unit of task. The completion duration is brought in the equation to account for different task processing times in design, build, commission.

Actor Project Participation
For(I=NofActors|(Step(1,StartTime+'Actor Entry Timing'[i])-Step(1,StartTime+'Individual Calendar Deadlines'[i])))*(min(1,{ArrSum('Total Actor Tasks'-'Net Work Done Design Stage')
,ArrSum('Total Actor Tasks'-'Net Work Done Build Stage')
,ArrSum('Total Actor Tasks'-'Net Work Done Commission Stage')}))

Logic: Actor participation takes as long as it is required to complete the tasks per stage. The assumption is that as rework reduces network done, actors spend more time to fix defects.

Actor Alignment Increase
For(i=NofActors,j=NofActors|'Actor Project Net Increase in Overlap'[i,j]
divz0'Actor Project Participation Duration'[i])*1<<mo>>

Logic: It is assumed that pressure and actor overlap brings the actors into alignment. This variable calculates a matrix of actor alignment.

Actor Alignment Decrease
For (i=NofActors, j=NofActors|max(0,'Actor Alignment'[i,j])/'Individual Actor Deadlines'[i])

Logic: It is assumed that as opportunity cost, i.e. other projects available in the building sector raise the pressure, alignment decreases with time.

Actor Project Interaction Rate Increase
For(I=NofActors|(Step(1,StartTime+'Actor Project Interaction Timing'[i])
-Step(1,StartTime+'Individual Calendar Deadlines'[3])))

Logic: This is to allow for project partners to be engaged in the project before they commit to work e.g. start work on site.

Actor Design -Build Communication Rate
('Actor Design Communication'[2]*'Com Priority at Design Stage'
'Actor Build Communication'[1]'Com Priority at Build Stage')*'Actor Design-Build Alignment'

Logic: The multiplicative logic is used to model the fact that both actors must reciprocally engage in communication (Bendoly and Swink, 2007). Additional communication on any of the actors is enough to have an effect on the understanding of the work that is being carried out. The same logic applies to *Actor Design-Operation Communication Rate* and *Actor Build-Operation Communication Rate*.

Inter Stage Information Increase
min({'Actor Design -Build Communication Rate','Actor Build-Operation Communication Rate', 'Actor Design-Operation Communication Rate', ('Max Info per Kind of Task'-'Actor Inter Stage Cumulative Communication'))/'Information Increase Delay'

Logic: It is assumed that a maximum information quantity per kind of project task is required to complete the task without any defects.

Information Decrease
For (i=NofActors| 'Actor Inter Stage Cumulative Communication'[i]/'Individual Actor Deadlines'[i])

Logic: The logic is that information decline is proportional to the participation of each actor. It takes a time period of participation to decrease information by about 66.6%.

Intra Stage Information Increase
min({'Actor Communication Design Stage','Actor Communication Construction Stage' ,'Actor Communication Operation Stage'},('Max Info per Kind of Task'-'Actor Intra Stage Cumulative Communication'))/'Information Increase Delay'

Logic: It is assumed that a maximum information quantity per kind of project task is required to complete the task without any defects.

Intra Stage Information Decrease
min('Actor Intra Stage Cumulative Communication','Actor Intra Stage Cumulative Communication' *max(1,{'Actor Alignment Design Stage','Actor Alignment Construction Stage','Actor Alignment Operation Stage'}))/'Individual Actor Deadlines'

Logic: It is assumed that information decline is proportional to the participation of each actor. It takes a time period of participation to decrease information by about 66.6%

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