Complex systemic failures in the Edinburgh Schools case

By Prof Jonathan Gosling, Prof Mohamed Naim, Prof Bill Hewlett, Stewart Macartney

Executive summary: In January 2016 an outside cavity leaf wall collapsed at Oxgangs Primary School during a storm, leading to wider school closures, disruption to learning, and widespread concerns about safety. Based on publicly available documents, the experience of the team, and academic frameworks, a retrospective analysis is undertaken. The failure was a consequence of deeper systemic issues, as well as assumptions about complexity. Changes are recommended in the areas of building standards, training, independent verification, collective sensemaking and 'self-reflective practice' by stakeholders and clients.

Tags: education infrastructure, building failure, wall collapse, mason wall-ties, construction quality control and regulatory compliance, fragmented procurement and supply chain, systems engineering change model, cynefin, cause and effect analysis, United Kingdom

Section 1: Background and introduction

In January 2016, an outside cavity leaf wall collapsed at Oxgangs Primary School when Storm Gertrude hit Scotland, leading to school closures, disruption to learning and widespread concerns about safety. Approximately nine tonnes of masonry fell at the school during the storm, leading to closures at Oxgangs, but also wider school closures to a further 16 schools for a period of months for investigation, structural surveys and remedial work. All these buildings had been built as part of the same Public Private Partnership contract with Edinburgh Schools Partnership Limited (ESP). The consequences were time and cost resources for remedial work, as well as disruption to children's education and communities. Luckily, there were no injuries or deaths, but this was purely a matter of luck as the collapse happened out of regular school hours. In addition, in the wake of the collapse, an initial BBC report revealed that 72 more schools in Scotland were found to have similar defects and judged to be unsafe (BBC, 2017).

The most obvious technical cause of the collapse of the wall was defects and poor-quality construction in the building of the wall. It was later found that it had failed to achieve the required minimum embedment for wall ties. However, as we will show in the case analysis, this failure arises from a combination of many deeper causes, exacerbating factors and assumptions. As was noted in the BBC's report, the failure was not a case of one or two rogue builders, but a consequence of much deeper systemic issues (BBC, 2017).

The Edinburgh Schools case is important for several reasons. The first is that it was 'avoidable'. An independent inquiry concluded that the failure was indeed 'avoidable' (Cole, 2017), since with better practices, designs, processes and approaches, the failure would not have happened. Secondly, it is not a single isolated type of event, and gives insight into a broader and more general problem. The interweaving failures in assumptions regarding complexity, minimum building standards, quality culture, oversight and commercial drivers established during the early phases of the project are likely recognisable across many building sectors and programmes of work. Thirdly, in the wake of the Grenfell disaster, building standards and quality failures are currently high-profile concerns. We consider that the case gives an insight into the way in which systems thinking can be used to approach such issues differently.

Based on a range of publicly available documents, and the experience of the team, we will analyse the stages of the lifecycle of the Edinburgh Schools case from original planning and design, through build and handover to post-construction operation. Taking the generic temporal phases of construction as a starting point, we structure our analysis based on an academic change model to classify the foci of activities and failures as being primarily of technology, process, commercial and attitudinal. In addition, to better understand the nature of systemic cause and effects in the case, we apply complexity frameworks to give generic insights into suitable management approaches. The analysis of the Edinburgh Schools case demonstrates how prevailing assumptions of simplicity in complex systems can lead to chaos and has potential for disastrous outcomes.

In the case analysis, we use and apply an existing sensemaking framework, named Cynefin, which is a classification that allows understanding of the 'habitat', or 'cynefin' in Welsh, within which the project is perceived to exist. **Figure 1** shows its domains. Cynefin classifies contexts that we may find ourselves in, in terms of Ordered, Simple and Complicated, and Unordered, Complex and Chaos. These domains have very different characteristics, especially in terms of the assumptions about the nature of cause and effect, and so it is evident that different managerial approaches are needed.

A common issue is that studies and tools and techniques tend to assume projects exist in a predictable world of cause and effect where things go according to plan. This often proves to be wrong, and chaos ensues. Our key message, however, is that management methods suited to a predictable domain are not wrong in themselves, but that they become so when applied in an inappropriate context, the unordered (complex) domain as Cynefin terms it. On this basis, a key message is that management methods or styles are not so much 'wrong' as 'wrong for their domain', so identification of the domain becomes critical for success. To determine which domain that we are 'in', the implication of which is to give a basis for agreement on the appropriate management methods and styles, usually requires an element of discussion, discourse and ultimately agreement or consensus among different stakeholders. Hence, we may actually find ourselves in a fifth disorder domain, where there is no shared understanding of which of the other four domains that we are in. If used effectively, the sensemaking framework can help to develop a shared understanding of the types of problems faced, their causes and solutions, agreed goals and targets, and identification of the appropriate problem-solving tools. Most importantly, it facilitates the 'right-sized' management tools, techniques and interventions for the specific situation faced, as well as self-reflection on our assumptions, helping to make them explicit.

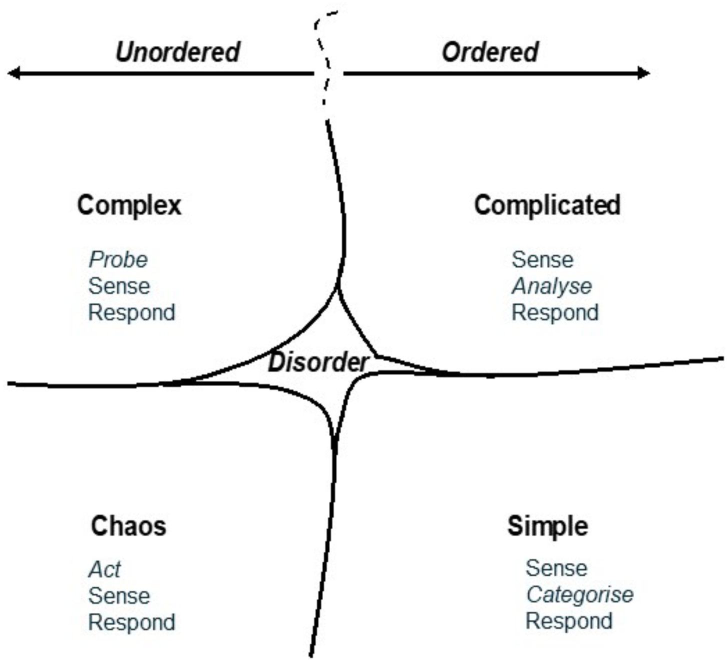

Figure 1: The Cynefin Sensemaking Framework (Kurtz and Snowden, 2003; Snowden and Boone 2007).

Building on a long line of research, Towill (2001) proposes a systems engineering toolkit to approach systems change. This consists of addressing four interacting systems change levers (see **Figure 2**). Here the constituent elements are technology, attitudinal, commercial and process changes. While there is often overlap, it is often possible to identify one or two primary change drivers. An integrated approach to systems change is proposed, but interestingly and highly relevant to our case, Towill argued that the changes count for very little unless a total quality management (TQM) culture is established throughout the supply chain. We utilize both of the above frameworks for analysis of the Edinburgh Schools case study.

Section 2: Analysis and insights

Complexity and the project stages

Figure 3 shows assumptions, misperceptions about complexity, and the shifting situations through project phases at Edinburgh schools. The initial and primary focus of the Edinburgh Schools inquiry was the failure of the cavity wall construction, so we focus on those elements, albeit in their wider context, as we analyse the project stages.

Planning and design

Early planning for construction work began in 1998 when the City of Edinburgh Council submitted an

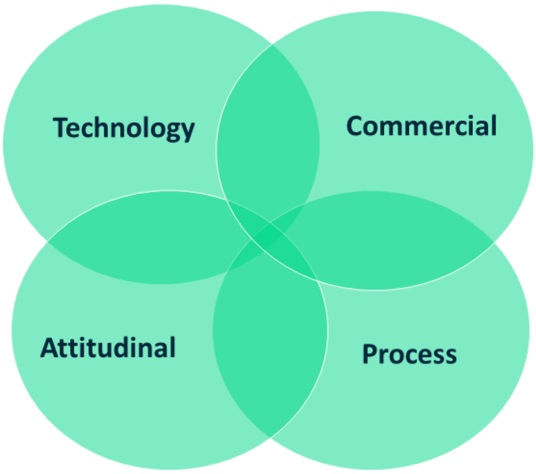

Figure 2: Systems Engineering Change Levers (Towill 2001).

Outline Business Case in support of a bid for revenue funding for a proposal to upgrade its Schools Estate through a Public Private Partnership (PPPI) model. The Full Business Case was approved in 2001. Responsibility for the design and construction of the schools was sub-contracted by ESP to a joint venture company formed by the Main Contractor and Facilities Management Company (AMJV). AMJV appointed two architectural firms and an engineering consultancy to undertake responsibility for the structural design of all 17 school projects. Tier 2 construction contractors effectively became sub-contractors to AMJV. Hence, the architects and engineers on the PPPI had no direct contractual relationship with the contractors employed to do the work and instead reported to AMJV. Furthermore, there were a large number of contractor-designed elements, rather than being made by the appointed engineers and architects, leading to split design ownership and lack of understanding (clarity?) of roles and responsibilities. Not long after the wall collapse, there was speculation as to whether PFI (sub-contracting?) arrangements push quality and design considerations to the margins, possibly emphasising economic drivers over wider public value, as well as separating designers from the responsibility to inspect their work (Marrs 2016).

At the design phase, the technological solution would have ranged from simple to complicated, bearing in mind that standards and systems exist for such solutions, even in non-standard locations. A structural engineer designed the structure taking into consideration the stability of masonry wall panels to ensure that they could withstand wind loadings arising from wind-speeds and loadings as currently prescribed in British Standard BS EN 1991-1-4: 2005 for use with PD 6697 2010, (BS 6399 applied at the time

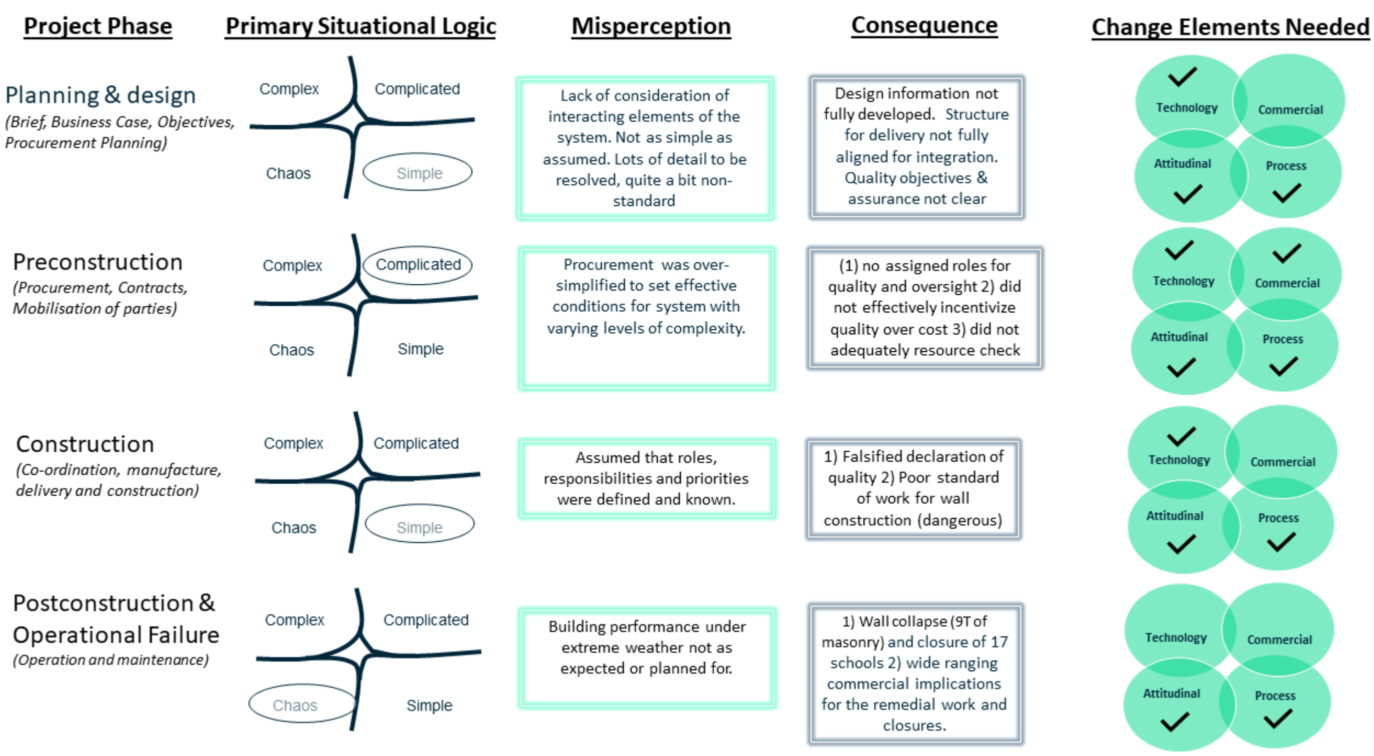

Figure 3: Analysis of project phases at Edinburgh Schools using Cynefin and Change Levers.

of the design of the PPP1 schools). Both standards take account of location, topographical exposure and orientation. Designs were 140mm inner leaf and 100mm outer leaf of either brick or rendered block. Some masonry panels had bed-joint reinforcement (BJR) specified for every course, some specified for every second course, and some unreinforced. Some were specified with wind posts as well as BJR. Investigations showed that many panels that should have had BJR had none, which dramatically impacted the strength of panels.

Cole (2017) points to a few issues at the planning and design stage. First, the structure allowed for key organisations to become one or two steps removed from each other, so that no proper relationship existed. This was the case between the designers, client, joint venture, and other contractors. Secondly, during the development of the brief, the quality objectives and approaches to ensuring quality could have been clearly defined at an early stage. A key misperception at this stage was the extent to which interactions (or lack thereof) between different elements of the design and delivery (organisational and technical) would simply work effectively without the right structures or provision in place. This led to design information not being fully developed, the structure for delivery not being fully aligned for integration or the delivery of quality objectives. An important misperception relating to the planning and design stage was the assumption that responsibility for elements and outcomes of the system, which were highly interdependent and complex, could be passed along layers of subcontracts without oversight. Changes to processes, attitudes and technology for design information are needed.

Preconstruction

During preconstruction, all formal communication to the Tier 2 contractors from the design team members in relation to the design and construction of the Phase 1 PPP1 schools, including drawings, specifications and technical requirements, had to be channelled through, approved and issued by design managers and project managers directly employed by AMJV. An Independent Certifier was appointed, but as noted by Cole (2017), quality assurance planning and procedures could have been clearer and there was no resource, requirement or provision for a Clerk of Works. Tendering processes are well known to be prone to opportunistic behaviour, especially when structured through layers of subcontracting, and a lack of design specificity at tender stage exacerbates the potential for error. A recognition of this complexity would suggest that arrangements to check outputs, skill levels and competency were as anticipated and the nuances of the work appreciated. Hence, during the preconstruction phase, procurement was oversimplified, and did not consider the interdependencies between elements and the drivers of different behaviours. For instance, for the procurement of masonry accessories, some were free issue and some were to be procured by the sub-contractor. This led to a lack of assigned roles for quality and oversight, did not effectively incentivise quality over cost, and did not adequately resource quality assurance. All four change drivers are needed to address issues during this phase.

Construction

Construction work took place during the early 2000s with schools in PPP1 beginning to be completed in 2004. Following a first phase of 13 projects, Oxgangs School was one of a second phase of four PPP1 projects completed in February 2005. These were constructed by Miller Construction, acting in the role of a Design and Build contractor. Cole (2017) notes that during the period of construction there was a general misconception as to the extent and purpose of site inspections undertaken as part of the Building Standards system. While visits to the PPP1 schools were undertaken by building officers, these were primarily focused on drainage checks. Key issues can also be identified in the overall coordination of the supply chain, and accessibility of design information to trades and subcontractors. This particularly applied to bricklayers and site supervisors. Although the construction of the cavity wall itself should be regarded as simple, two key factors highlighted by the report that contributed to the deviation from standards were the lack of design information by which the brick layers could have determined the depth at which the ties were set into the leaves and the payment mechanism for the brick layers (Cole, 2017). There was also poor coordination of information and details between architects' drawings and engineers' drawings with some conflicting information, leading to confusion. Hence, during the construction phase, there was an assumption that roles, responsibilities and priorities were defined and known. In particular, responsibility for checking and verifying standards slipped between the gaps. Full availability of information was not accessible at all times. This led to a falsified declaration of quality and poor standard of work for wall construction. Changes to processes, attitudes and technology for design information are needed.

Postconstruction and operational failure

Following the wall collapse, council officers closed the school with immediate effect, and structural engineers were appointed to provide advice relating to further risks to safety that might be associated with the collapse and possible remedial work. A visual inspection and report on the external walls of all 17 PPP1 projects was also requested. Subsequent inspection and analysis identified a combination of excessive cavity width, related non-verticality and incorrectly constructed wall ties, missing BJR and wind posts, missing wall head restraints, as well as panel edge ties back to primary structure and columns. This resulted in a cavity wall construction in which many of the ties had insufficient embedment in the outer leaf.

This represents chaos in the immediate aftermath of the collapse: What are the implications of the collapsed wall? What do we do? The second follows rapid intervention by the City of Edinburgh Council, which closed the School, transitioning the situation (at least as far as the authorities were concerned) into the Simple domain. There then followed an interesting period (Disorder) during which there was no consensus on the severity and urgency of the situation. During this period, the school remained in use, but subject to expert structural monitoring and a constant weather watch (a Complex arrangement for structural engineers; Chaotic for teachers who had to work around these unsatisfactory arrangements; Simple for pupils (the school was open, get on with it and do as you're told), and Complex going on Chaotic for contractors who had to recognise they had a problem with unforeseeable potential outcomes. Meanwhile the City Council, school governors and staff, contractors and structural advisors sought consensus on what to do and how, constantly abated by parents and the press). Following this, a further phase, which began as Complex but later became Complicated, during which Oxgangs and the 16 other schools within the same PPP programme were investigated, closed or partially closed and remediated; continued until August 2016. Accomplishing this involved bussing pupils to different locations and redeploying staff accordingly – an exercise at the limit of what can be defined as complicated. Process and attitudinal changes are needed to drive change.

Causes, consequences and exacerbating factors

Figure 4 shows causes, consequences, outcomes, exacerbating factors and controls.

Causes and exacerbating factors

The diagram highlights two primary and underlying causes, both

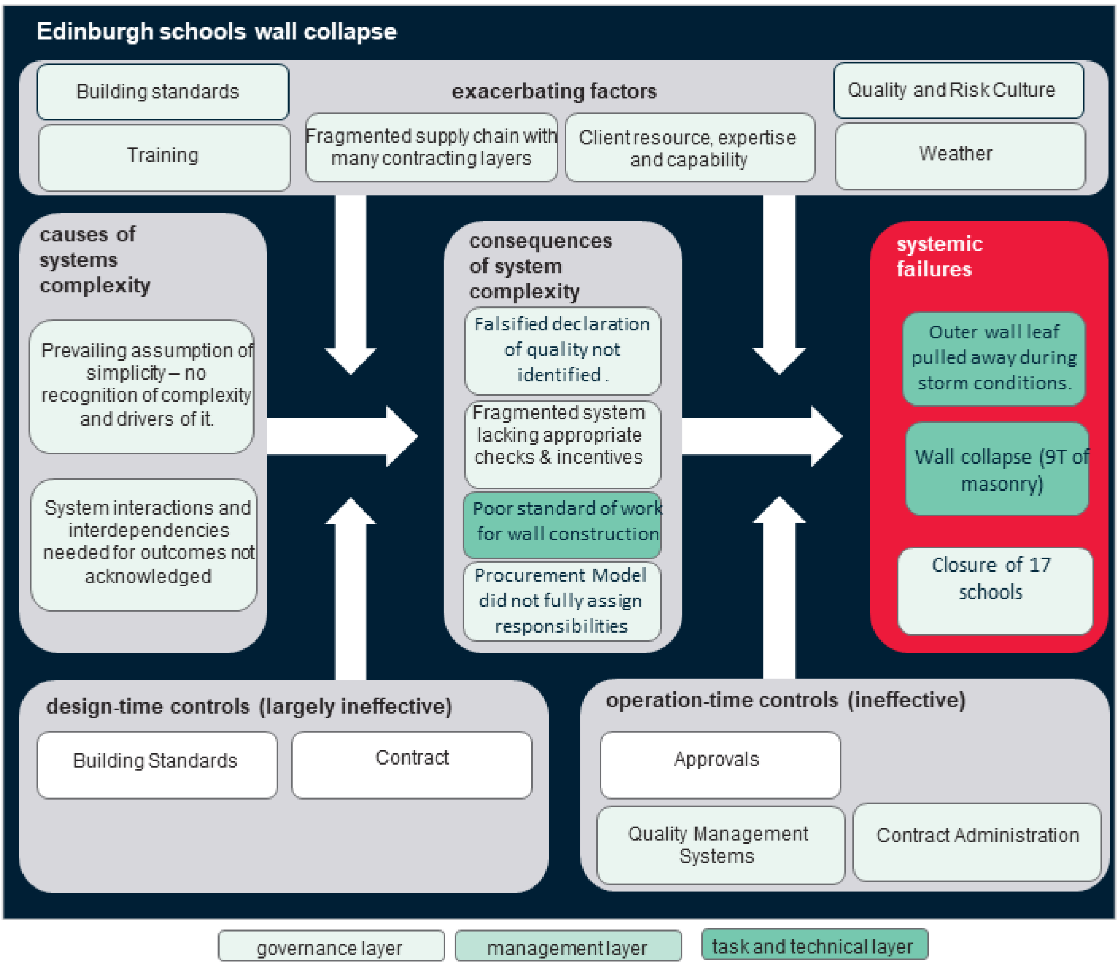

Figure 4: Analysis of causes, consequences, outcomes, exacerbating factors and controls.

related to 'mindset' at the time of the project. Firstly, the assumptions relating to complexity. A range of aspects across project phases were oversimplified, so that solutions for a 'simple situation' were applied (Naim et al., 2021). Oversimplifying left design details unfinished and responsibilities unassigned. Secondly, the picture that emerges from the project phase analysis presented in figure 3 is that a series of omissions, oversights and assumptions gather and creep towards large scale problems. From the outset, these interactions and interdependencies were not adequately considered. As noted by a commentator at the time:

> *"There are systems in place that are supposed to pick up these issues going through – but that relies on everyone in the chain to do what's expected of them. And when things get missed, that can have an impact further down the chain, and ultimately I think that's part of what's happened here"* (BBC, 2017).

Through early planning and procurement, assumption about drivers of behaviour and quality standards were made, which cascaded through the design phase, where designs were not fully detailed or accessible, and into mobilisation phases, where interface issues arose, collaborative links were not formed, and an environment formed in which poor construction work could pass through unchecked. Ultimately, bricklayers did not follow process or adhere to standards, and the checkers did not conduct effective verification.

There are a range of exacerbating factors, which inflamed the above issues. Building standards are often treated as minimum standards, and the standards articulated in design are often separated from the administration and management during the construction phase. Supply chains are typically based on short term or one-off relationships in the construction industry, leading to fragmentation. This is exacerbated by layers of subcontracting. In addition, sadly, the quality culture that is seen across some areas of the manufacturing sector (based on Total Quality Management) is very often not replicated across the construction sector, where quality is often perceived as someone else's responsibility to check. Client resource and expertise may also have been a factor in terms of monitoring and control, but also assigning responsibilities and managing the overall programme. Finally, the weather: the wind speeds in Edinburgh on the day of the collapse were high, but not in excess of design expectations.

Consequences and systemic failures

The City of Edinburgh Council, in common with the majority of other public sector clients undertaking PPP projects for the first time, oversimplified the procurement process, for example by not appointing Clerks of Works to provide inspection services. The public procurement conditions did not establish the right incentives for a safety or quality culture to flourish. Economic decisions by the contractors were focused on small savings and commercial incentivisation of bricklayers, based on the number of bricks laid rather than on the value of work done; bricklaying is more complicated than simply 'laying bricks', and value will not be achieved if perimeter fixing details, and various mid-panel details, are not installed correctly. This led to perverse incentives, encouraging the omission of elements providing the essential structural integrity of walls. The failure to incorporate the ties, restraints and joint reinforcements, in accordance with the design, impacted significantly on the capacity of the panels to resist the required levels of wind-loading and undermined the integrity of the structural design of the external walls of the schools. The PPP1 contract contained a requirement for the preparation, provision to the council and maintenance of as-installed drawings and related documentation. This provision was not adequately complied with. Guarantees of adequate quality were also false. Checking and administration of standards was disjointed.

Section 3: Discussion and transferable learnings

What went wrong? What should have been done differently?

Section 2 highlighted a wide range of factors that interacted and led to the wall collapse. From the analysis of project phases in section 2a, it is possible to see the gradual build up and knock-on effect of omissions and assumptions as they cascaded through the project phases. Through the systems analysis of causes and consequences in 2b, it is possible to see that project failings were also positioned within a particular context, whereby they were inflamed by a range of exacerbating factors and underlying assumptions.

Design and operation time controls should have addressed these failings and issues more effectively across the project phases. A better level of detail in the design drawings would clearly have helped, but this prompts some interesting discussion points: What level of detail was needed in the design drawings? How should the level of design detail have been verified? How could overlap between architectural and information shown on architects' drawings and information shown on the engineers' drawings have been managed and integrated? Controls to improve collaborative structures between clients, designers, contractors and subcontractors, so that organisations are not removed through many decoupled layers, and better integration of the supply chain, would have helped to clarify roles and responsibilities and develop more proactive information sharing mechanisms. A clear area where system controls would have helped avoid the failures is the clarity and articulation of a strategy and process for independent oversight, checks and verifications at different levels. How should work in accordance with the design, and accepted good workmanship, have been verified?

What can the industry learn from the Edinburgh Schools case? What are the broader transferable lessons?

Following the independent inquiry into the Oxgangs school wall collapse, a broader review of building standards was undertaken in Scotland (Cole 2018). This latter review found that Oxgangs did indeed represent non-compliance with the requirements of the Scottish Building Standards and suggested that steps were needed to strengthen adherence. In particular, there is a need for verifiers and applicants to fully understand and deliver on their responsibilities. Cole (2018) points towards culture change through education and training as a key area for change. A related area, which Cole (2017) alludes to frequently in the independent inquiry, is the value of experienced Clerks of Works, an area of expertise that will need to be cultivated and promoted through training if they are to be used properly in the future. However, even with these changes much work is required to foster the Total Quality Management culture seen in other industries.

A key implication of our preceding discussion on the Cynefin complexity domains and the systems engineering change levers is the importance of collective sensemaking by stakeholders and clients to avoid making overly simplistic assumptions. The desire for situations to be determinate and simple, so that spreadsheets, documents and plans can be drafted with certainty is understandable, but this is often unachievable in practice, so governance approaches and incentivisation models must reflect that. A broader lesson to be learned, therefore, is the importance for leaders and teams to routinely examine and reflect on their assumptions at critical decision points. Such 'self-reflective practice' to explicitly articulate assumptions, and develop any potential mitigation plans, can be encouraged through the project governance processes. For instance, through assumption mapping at the planning stage, monitoring and control processes as the project progresses and then project learning logs and retrospectives to better understand the impact of assumptions made. An interesting discussion point is that decisions are often taken without their criticality being realised at the time, therefore the mindset for self-reflection needs to be cultivated. This could also be anchored within the project phases of planning, design, construction and operational and maintenance, as per **Figure 3**. In doing so, we hope that designers and contractors think beyond small, scoped packages of work and completion of a project, towards broader longer-term value.

Some concluding thoughts are offered via a summary of necessary changes required with references to the change levers discussed earlier in the case:

- Process – changes are needed in the procedures to assign responsibilities for oversight and independent verification, as well as mechanisms for accessibility of up-to-date and detailed design information. Conditions of engagement, as set out in the procurement strategy, would be better articulated to align the roles of the various supply chain actors. Process improvements could also be facilitated via design checklists and responsibility matrices for design and construction. In addition, formal gateways and review stages in building standards within the process, which also prompt leaders and teams to make their assumptions explicit, would help control safety critical works.
- Commercial – reform is needed to align economic incentives and drivers with project aims, taking into account complexity and uncertainty as project phases progress. Deeper understanding of the behavioural implications of procurement decisions on trades and contractors, as well as site activity, is needed.
- Technology – new digital technologies provide new opportunities for open access and standards for designs. Alternative forms of construction, with greater offsite use, may reduce the possibility for human error. Offsite approaches are becoming a major focus due to the ability to verify system elements, offer better quality control and working environments, as well as address labour and skills shortages. However, this needs to be balanced against the risk of fragmentation of procurement, increased criticality of element interfaces, and alternative modes of systemic failures inherent in new technologies.
- Attitudinal – broader changes are needed to reconsider assumptions regarding simplicity and complexity, so that planning and procurement strategies devote due acknowledgement of complexities and the risks and implications flowing from it. Further attitudinal changes are required for a positive quality culture to thrive, and finally changes to assumptions about the nature of interdependencies, particularly through better

adoption of supply chain integration practices. A greater level of self-reflection and examination of assumptions at critical decision points is needed, leading to more explicit articulation of premises relating to complexity and corresponding mitigation plans. Training will likely play an important role, at the level of leaders and teams, but also more specifically targeted at bricklayers and trades so that there is an increased awareness of technologies and the broader safety implications and impacts of work undertaken, as well as expected values and behaviours.

This case study has provided a retrospective analysis of a project with significant failure. It is important to look back and learn from such events. Many industries are now using a 'manage by projects' approach and it is possible to see from the Edinburgh Schools case that there is a shifting landscape through complexity domains as the project proceeds and problems build though interdependencies. Occasionally, problems will align in such a way that a critical failure arises. A mixture of attitudinal, technology, commercial and process-based system changes can minimise the potential for this to happen, but this needs input from professional communities of practice, standards, as well as education and training. It also needs a willingness to be self-reflective and examine our assumptions at critical decision points and we hope that this case provides guidance for doing so. Given the depth of impact of some of the exacerbating factors discussed in the case (for example fragmented supply chains with layers of subcontracting focused on short term costs), there is a need to understand the systemic nature of the problem, which we hope has been highlighted in this case, and then develop a systems-based response to drive system actors and behaviours towards the desired outcome.

How using the Cynefin framework and systems engineering approach helped us to analyse the problem

Finally, we offer some reflection on the value and utility of the Cynefin framework in helping to illuminate the problems in the case, and how it might help in other situations. In the case, we used the Cynefin domains to show a changing landscape as the project phases drifted in and out of situations with different characteristics and any misperceptions observed. A key distinction made was the cause-and-effect chain for different contexts: cause and effect are relatively stable in the simple domain and then get less stable in other areas of the framework and the differences call for different and appropriately tailored management approaches. Retrospectively, it is possible to observe fundamental misperceptions of those involved in the case seeing some situations in the system as simple when there were elements of complexity to be managed.

The Cynefin framework probes and surfaces assumptions relating to changing situations, as well as providing a language to articulate them. This, in turn, helps to challenge deeper habits and mindsets and to offer a basis for preparing a response to situations. It is possible that we can never fully know with certainty all elements of the system and we argue that there is a risk of oversimplifying and not developing system capabilities and mitigation and contingency plans for less predictable and/or uncertain elements. Embedding the Cynefin approach into planning and monitoring processes will help teams to sense make and articulate their assumptions and plan appropriate responses. The systems engineering change levers adopted in the analysis of the case provide a practical categorisation of possible initiatives and actions. We encourage considerations of complexity, process, commercial, technological and attitudinal to be explicitly addressed in risk assessments and project management processes.

Further reflections and lines of enquiry

The lack of training, education and understanding of the significance of the masonry accessories by the bricklayers was an important cause of the failure. Unless that is addressed, no amount of systems or checks will address fundamental effective ownership of quality. Quality must start with those doing the work, but how can training be effectively embedded?

Safety critical elements and items must be treated, checked, monitored and verified. However, effective verification is a major challenge. What records are needed and how should they be obtained to ensure and demonstrate compliance?

Product specification, standards and quality requirements often contain conflicting information, specifications and inconsistent levels of detail. How should safety critical components be specified, detailed and communicated at all levels?

Many sub-contracting organisations have questionable quality systems. Reliance is often placed on the quality management systems of the principal contractor. This fragmentation, and misunderstanding about the nature of quality management, often leads to quality being a burden or cost to be passed along. What types of contractual relationships, contracts and metrics are needed and which procurement strategies can best support quality improvement? How can a Total Management Culture be successfully embedded in the construction industry?

References

BBC, 2017. Defects found at 72 more Scottish school buildings. https://www.bbc.co.uk/news/uk-scotland-scotland-politics-39580308

Cole, J., 2017. Report of the Independent Inquiry into the Construction of Edinburgh Schools.

Chartered Institute of Building's Policy and Public Affairs. https://www.thefis.org/wp-content/uploads/2018/08/Edinburgh-Schools-report.pdf

Cole, J. 2018. Report of the Review Panel on Building Standards Compliance and Enforcement. https://www.gov.scot/binaries/content/documents/govscot/publications/corporate-report/2018/06/report-review-compliance-enforcement/documents/00537870-pdf/00537870-pdf/govscot%3Adocument/00537870.pdf?forceDownload=true

Marrs, C (2016). Did PFI cause Edinburgh's school failures? https://www.architectsjournal.co.uk/news/news-feature-did-pfi-cause-edinburghs-school-failures

Naim, M. M., Gosling, J., & Hewlett, B. (2021). Rethinking infrastructure supply chain management – a manifesto for change. *International Journal of Logistics Research and Applications*, 1-22.

Kurtz, C. F., & Snowden, D. J. (2003). The new dynamics of strategy: Sense-making in a complex and complicated world. IBM systems journal, 42(3), 462-483.

Snowden, D. J., & Boone, M. E. (2007). A leader's framework for decision making. Harvard business review, 85(11), 68.

Towill, D. R. (2001). The idea of building business processes: the responsive housebuilder. Construction Management & Economics, 19(3), 285-293.

Acknowledgements

This work was supported by a grant from the Safer Complex Systems mission of Engineering X, an international collaboration founded by the Royal Academy of Engineering (the Academy) and Lloyd's Register Foundation (LRF). The opinions expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Academy or LRF.

Affiliations

Prof Jonathan Gosling, Professor in Logistics and Operations Management, Cardiff Business School, Cardiff University

Prof Mohamed Naim, Professor in Logistics and Operations Management, Cardiff Business School, Cardiff University

Prof Bill Hewlett, Honorary Visiting Professor, Cardiff Business School, Cardiff University and Technical Director, The British Board of Agrément

Stewart Macartney, Director, Blyth and Blyth Consulting Engineers Limited