Biological Cell Theory based Interventions and the Impact on Quality: The Case of a Tower Project

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Abstract:
Inspired by the almost defect-free proliferation of biological cells, authors have explored the notion of 'construction as biological cells' metaphorically to develop new insights on how to manage quality. Three concepts, namely, 'transient cell cycle arrest (TCA)', 'readiness check', and 'embedded design' were used as interventions to manage the quality of three problematic core activities in a large transmission tower project. Action research method underpinned the investigation with the first author as a participant. TCA was triggered by non-compliance reports (NCRs) of the Excavation cell with an improvement in quality. 'Readiness-checks' were effective with the Concrete Supply cell not reporting any NCRs. The 'embedded design' for the Steel Tower Assembly cell embodied 'prototyping before cell propagation, lessons-learnt imprints, cell readiness checks, constant surveillance mechanisms, feedback and feedforward loops, and product traceability systems' with only two NCRs although no TCAs were initiated raising questions when to initiate NCR based TCAs. These issues are to be explored further. It is argued that these interventions may have had an impact on lowering rework costs below the project threshold level with the project adjudged as the winner of the contractor's national award for project excellence.

Keywords: Biological cell theory, embedded design, transient intervention, quality management

6. INTRODUCTION

The biological cell theory states that all living organisms are composed of similar units known as cells. These cells proliferate through division creating multicellular organisms. Inspired by the almost error-free replication of biological cells (Karp, 2010) to develop multicellular complex structures, Abeysekera and Shelke (2015a, 2015b) have explored the metaphor of 'construction as biological cells' to develop new insights on quality management. They endeavour to pursue this notion further through this paper by examining the application of some basic principles of biological cells on a real construction project.

7. The Transmission Line Tower Project

The project involves the construction of a 57km of double-circuit 275kV transmission line, foundations for the towers with supply and erection of tower steel, and stringing of the conductors between two substations valued at Australian $ 35million. It also involves a 2km of 132kV double-circuit transmission line to the gas plant. The self-supporting steel lattice towers are fabricated from galvanised steel members, steel plates and are bolted together with heights ranging from 10 meters to 58 meters to span watercourses or native vegetation or larger distances over relatively benign topographic profiles. The weight of the towers range from 36 tonnes to 65 tonnes with a span of 150m to 600m between towers which are strung with client supplied conductors. There were 147 towers with 3500 tonnes of galvanised tower steel used. Each tower had four legs which were supported on reinforced concrete piled foundations using 3300 cubic meters of concrete. The contractor executing this project is one of the largest construction companies in the world with a history of executing such high voltage transmission line projects.

8. An Introduction to the Metaphorical Approach

As noted before, inspired by the almost error-free proliferation of biological cells, authors have taken a metaphorical approach by exploring the notion of 'construction as biological cells' taking the position that construction cells are similar to biological cells in certain ways although different in other ways (Abeysekera and Shelke 2015a, 2015b). This approach labelled as the Metaphorical Approach has permitted the authors to develop new insights on quality management in construction with this paper exploring the relevance of three concepts. It needs to be noted that similar approaches have been used before by Deleuze and Guattari (1987) and advocated by Midgley, Trimmer, & Davies (2013).

9. Biological Cell Theory and its Relevance to this Study

Three concepts, namely, 'transient cell cycle arrest (TCA)', 'readiness check', and 'embedded design' have been identified for further exploration. These are explained further in the following sections.

4.1 Transient states of rest

Biological cells proliferate through cell division. The process is controlled through a mechanism which goes through four phases in a cyclic manner (see Fig. 1) and these phases are described in Table 1 (see, Bartek, Lukas, & Lukas, 2004; Kastan & Bartek, 2004; Reece et al., 2012). Interestingly, the process is also kept in tab through three checkpoints as shown in Fig.1. These checkpoints act as gates with the capability to stop the process. If the process is defective, it puts the cell into a transient state of rest until it is ready for replication. In the event it is found replication is not possible without error, the mechanism ceases to function by causing cell death.

Table 1: Cell cycle phases and cellular control of activities

Stage	Cell Activity	Control of Cell Activity
G1	Initial state at rest waiting for a signal from Growth factor to proceed to next stage for proliferation. The cell grows, carries out Metabolism.	Checkpoint G1- in place and will delay progression to next stage in case of damage to DNA and repair damage. Checks for cell size, nutrients, growth factors. Commit to next stage on passing the checkpoints else leave the cell cycle and enter resting state called G0 phase- Resume dividing if conditions improve.
S	Replication of DNA.	Irreversible phase where DNA replication occurs. Surveillance mechanism for detecting errors, delaying replication and initiate repairs. Allow recovery of cell cycle progression after repairs
G2	Cell grows and prepares for mitosis	Checkpoint G2- for cell size and DNA replication, damage. Confirm DNA integrity following replication in S phase. Pause and allow for repairs if required by halting cell cycle. Induce apoptosis or programmed cell death to ensure damaged DNA is not passed onto daughter cells
M	roduce two nuclei each with complete. Copy of entire chromosome in original cell	Checkpoint M- for chromosome-spindle attachment. Will arrest cell cycle if found unsatisfactory

Interestingly, there are other checkpoints as well. For example, when a cell moves into the S phase, to ensure that the purpose of that stage is achieved correctly, the cell mechanism has additional checks to slow down the process providing time for repair through a surveillance mechanism. In construction, this refers to a situation where the production process has started but is temporarily halted due to the presence of a number of NCRs (see Intervention 1 discussed in Section 6).

4.2 Readiness for replication (at start)

The cells subdivide in the M phase, and as noted in Table 1 it moves into the G1 phase where the newly divided cells keep growing. However, the most important stage is the S stage where DNA is replicated. Because, according to Cassimeris, Lingappa, and Plopper (2011) the production of new cells require the division of the pre-existing cell, a cell must carry within it the information for reproducing all of its components (which the authors refer to as the embedded design, section 4.3). For this to happen accurately, the preparatory stage is important for launch this phase. There is a checkpoint for the cell readiness for this crucial stage in the cell cycle for replication of genetic information. Cell attributes like the cell size, nutrients, growth factor, the status of the existing DNA for replication is checked and repaired if required. The checkpoint will arrest participation in cell cycle till satisfactory readiness is achieved. In a construction situation, this is similar to where a concrete production plant is thoroughly examined for the capability or the ability to produced quality concrete and its production capacity (see Intervention 2 in Section 6).

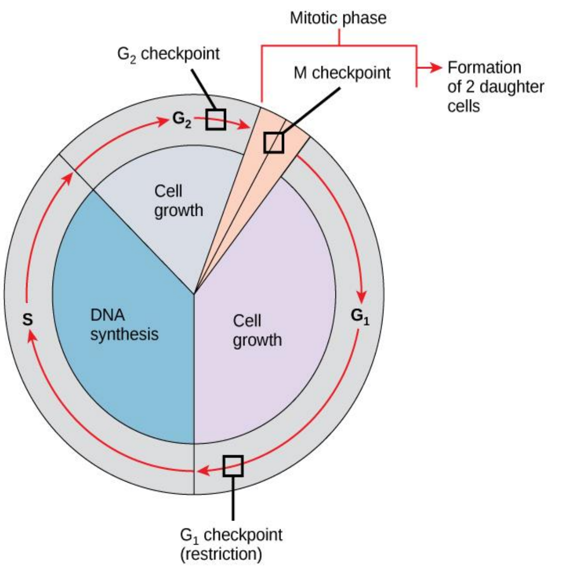

Figure 1: Cell Cycle Phases G1-S-G2-M and Checkpoints
Source:(Boundless.com)

4.3 Embedded Design

The nucleus houses the genetic information necessary for cell growth and reproduction according to Alberts (2012), and the cells possess means to use the genetic program which is constructed of DNA (Karp, 2013). According to Karp (2013) the cellular activities can be remarkably precise with the DNA duplication error rate of less than one mistake every ten million nucleotides incorporated, and most of these are quickly corrected by an elaborate repair mechanism that recognises the defect. The human genetic program providing information to build has enough information coded to fill millions of pages of text if converted to words and these constitute the blueprints for constructing cellular structures, the directions for running cellular activities, and the program for making more of themselves (Karp, 2013). The above is a description of what the authors refer to as the embedded design, which is not only driving the very processes for efficient cell replication, but the design is also passed onto the next replicated cells with high fidelity. In construction, a similar situation is the coded instruction in the various project documentation and the processes to implement the procedures to achieve error-free replication of the construction cell (see Intervention 3 in Section 6).

10. Aims and Objectives

In the preceding section, reference was made to three BCT concepts, namely, transient cell arrest, readiness for cell proliferation, and embedded design. The intention of this paper is to discuss the relevance of these concepts to quality management, particularly on how these concepts were applied for managing quality in the tower project described above with the intention of understanding how these concepts could be used for the management of other projects.

6. Methodology

6.1 Cell identification

Fundamental to the application of the above concepts was the identification of suitable cells. Abeysekera and Shelke (2015) have noted before that cells could be identified in different ways. In this project, cells were identified based on repetitive physical tasks such as excavation of footings for the towers. Given that there were many cells, it was not practical to trial the application of these concepts to all such cells. According, following discussions with senior project team members, it was decided to focus on cells that were considered significantly risky in relation to quality, time and cost overruns. Accordingly, the following cells were identified informed by the experience of completing a similar project recently: (a) Excavation cell (b) Concrete supply cell (c) Tower steel erection cell

6.2 Research methods

The first author of this paper was involved in this project as the Senior Quality Coordinator. Accordingly, it was thought opportune that an attempt is made to apply these concepts in discussion with the project staff. Participatory research methods such as action research seemed appropriate. According to Reason and Bradbury, as cited in Brydon-Miller, Greenwood, and Maguire (2003) action research have been described as seeking 'to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people…' This method challenges the claims of a positivistic view of knowledge which holds that in order to be credible, research must remain objective and value-free, with Brydon-Miller et al. (2003) insisting that values require actions and knowledge comes from doing, and it is this knowledge which is compelling the action researcher to act. Action researchers plan for cycles of action and reflection and thereby must be reflexive about how change efforts are unfolding, and the impact that our presence (the intervention) is having (Bradbury-Huang, 2010). Berg, Lune, and Lune (2004) have cited three types of action research identified by Grundy (1988, p.535), Holter and Schwartz-Barcott (1993, p.301) and McKernan (1991, pp. 16-27) while categorising these into three types of action research: (a) a technical/scientific/collaborative mode (b) an emancipating/enhancing/critical mode, and (c) a practical/mutual collaborative/deliberate mode. The latter method was employed in this project as the researcher and practitioner came together and collaboratively identified potential problems and issues, their underlying causes, and possible interventions. The first author (as a participant) planned and carried out a number of interventions in an ongoing project with the analysis of such interventions carried out to gain post-intervention insights. Such interventions were carried out in a collaborative manner. It is important that when the study is over, the stakeholders still need to know what the results were as per Berg et al. (2004) which will be carried out in due course.

On the weakness of action research method Brydon-Miller et al. (2003) refer to the 'localism' where the bulk of action research, while often doing much good in the local situation, however, fail to extend beyond the local context. Bradbury-Huang (2010) have concerns regarding the generalizability of this approach. In response to such concerns, Brydon-Miller et al. (2003) affirm action research is much more able to produce 'valid' results than conventional social science research because expert research knowledge and local knowledge are combined with local stakeholders involved in the process. Also, it is stated that this method meets criteria of validity testing more effectively than do others forms of social research because such projects test knowledge in action. Bradbury-Huang (2010) also counter such criticism about generalizability drawing attention to the growing accumulation of local knowledge and has suggested sharing such local knowledge through a peer review mechanism with the possibility of transferability of knowledge.

6. 3 Interventions and Inductions

Any intervention in the existing QMS (Quality Management System) to a project can be challenging as it questions the status-quo and the accepted manner of working. To overcome this, the first author had presented the concept of BCT and its likely potential to achieve quality in construction to the Senior Project Manager and Construction Manager. This induction allowed the application of such intervention in the project to be done in a collaborative manner. The three interventions are described next.

Intervention 1: Transient cell cycle arrest (TCA) of Excavation Cell (including concreting))

This intervention is connected with the Excavation Cell to arrest the recurring rework due to quality issues and to achieve synchronisation with other processes like procurement and timely delivery of reinforcement steel, and concrete supply. In all, there were 147 towers. By the time the first author joined the project, foundation excavations of 20 towers had been completed (i.e. a total of 80 pile foundations as there was four per tower). The excavation of the foundation required a specific inclination angle, depth, and dimensions. However, the excavation cell had quality issues which were recorded in the non-conformance report (NCR). These reports would record quality defects with details on its cause (if known), corrective action to be taken, and the cost of such work. Although not all NCRs will incur rework costs, this study focusses on those NCRs that resulted in rework.

There were five non-conformances recorded. One each for the incorrect inclination of the bored hole, excavation at the wrong location, concrete not placed in the excavated foundation hole within 48 hours of excavation due to issues with supply of reinforcement cages, and the incorrect diameter of excavated foundations leading to insufficient concrete cover (two instances). Such issues caused delays in the propagation of the excavation cell because the non-conformances to the specification required rework thus holding up the subsequent activities like placing of the reinforcement cages and subsequent concrete works. The trigger for the intervention was the non-conformance reports requiring rework, As the number of NCRs were considered high, this cell was put under TCA, and all activities related to this cell was deferred until all problems were fixed. Although this work stopped caused delay, it allowed for synchronisation of other processes, for example, allowing for delivery of the required reinforcement cages. While the propagation of excavation cell was in a state of rest, the process was refined till quality parameters were achieved. The problem was rectified by replacing the machine operator and the attachments used for excavation.

In summary, a state of transient cycle arrest was induced (as per BCT) for fixing all issues before the excavation cell cycle was allowed to take part in further proliferation. The impact of this intervention was the propagation of excavation cell across the balance 127 towers (i.e. 508 excavation sub-cells) with minimal quality issues as discussed later in Section 6, Results.

Intervention 2: Concrete supply cell readiness (for production)

The onsite batching concrete plant was the key to the quality and timely supply of product because within 48 hours of excavation the concreting activities had to be completed as per contractual requirements. While the initial mix design was approved by the client, there was a need to ensure further the batching was capable of providing a continuous supply of acceptable concrete. This second intervention was for the concrete supply cell to ensure the cell was ready for taking further part in propagation or construction in an error-free manner. Abeysekera and Shelke (2015b) have described this G1 checkpoint in the cell cycle control mechanism in Figure 1 above as the mobilisation and mobilisation checkpoint for confirming the readiness of the cell before taking part in replication.

An exhaustive audit on the batch plant based on the NRMCA (National Ready Mix Concrete Association) guidelines with suitable checklist prepared was conducted to confirm the readiness of the plant before the supply of any concrete to the project. Based on observations and review of the production process, action items were raised on the calibration of flowmeters and weighing scale, concrete testing register, aggregate testing report and summary report for the non-conforming product at the plant and preventative actions. It was only after initiating satisfactory actions to complete this, was the plant allowed to supply concrete to the project. Thus, in accordance with the BCCM concept, the cell is checked for proper 'growth' or capability to take part in the cell cycle for propagation or supply of concrete. While the initial readiness checks on the plant were detailed in nature, ongoing regular surveillance of the batching plant and regular review of the concrete test result ensured major quality risks associated with the concrete quality were addressed, resulting in the error-free supply of nearly 3300 cubic meters of concrete to the project.

Intervention 3: Embedded Design for Steel Work

This intervention is based on the concept of embedded design which has instruction for accurate replication of the cell. It requires decoding of the instructions and following the processes and procedures to achieve **proper construction and replication of cell**, the instructions for which are embedded in various project documentation like design, processes, and procedures (Abeysekera & Shelke, 2015b).

The supply of the Tower Lattice Steel was considered as critical because the steel was fabricated overseas (3500 Tonnes) with each Tower later assembled on site. Any fabrication error or missing part would take longer to fix given the longer lead time of 6-8 weeks for replacement of correct part from the overseas vendor. The contract did require the construction of a *prototype or initial cell* which was completed. Accordingly, this was an essential feature of the embedded design, i.e. the construction of an initial cell. On reflection, this was quite useful for understanding and validate construction processes but not management practices. Interestingly, further investigations need to be done to understand the value of this practice through a cost-benefit study, when such a practice should be used, and how its value may be enhanced. There was an external audit organised too at regular intervals starting at the overseas fabrication facility with an experienced person representing the contractor ~~was~~ present to authorise the dispatch of the finished steel. It is seen as a gated check as in biological cells. These steps were already implemented before the first author joined the project as the project staff had learnt from mistakes in the recently constructed project (referred to earlier). Thus, yet another feature of the embedded design is to incorporate a mechanism to ensure that there is a deliberate attempt to learn past projects and make necessary changes to the previous 'embedded' design. Given the significant negative impact of a potential quality issue (this cell was seen as highly risk cell as noted before), the first author introduced the following features to the embedded design:

Pre-checks: It needs to be noted that the embedded design for this cell was modified (from that used in the previous project) to include additional pre-checks of the delivered steel at the port of delivery in Australia before its onward journey to the site. Each component was barcoded and the delivery status of the steel tracked in real time. A visual check for every component of steel delivered on site was introduced to check for any damages to protective coating, the presence of rusting, and any handling damages with provisions made for immediate correction of identified defects. The site crew was specifically instructed not to proceed with the erection in case of any quality issues were discovered during pre-assembly. Proceeding with construction with any defects however minor they were barred because any fixing of such defects would entail costly rework requiring working at heights to disassemble the steel and carry out any repairs.

Constant surveillance: It is noted that *constant surveillance* is another feature of the embedded design of the biological cell. Transferring this notion to construction means that high-risk cells need to be subjected to a constant surveillance regime. Accordingly, the steel tower erection cell was closely monitored for strict compliance with the embedded design (including the activity method statement). Surveillance carried out by the client as well with a system set up to record and respond to any issues raised.

Feedback and feedforward loops: A centralised recording system was installed and managed by the first author on site for any steel related issues with feedback on the steel issues on site channelled through the Senior Supervisor who confirmed the quality of the steel and its location on the site. It assisted in reducing duplicate feedback from other crew members and improved the accuracy of feedback because a single person was accountable for confirming and forwarding the issues for further actions. This approach improved the communication across the sites will all feedback actively sought, filtered and channelled for further action. Such effective cellular communication is one of the features of the embedded design.

Product traceability systems: A centralised tracking system for steel issues was introduced with status available to relevant stakeholders including a link with the local fabricator for immediate repairs, and especially for sourcing any missing parts.

All these features could be seen as elements of the revised embedded design. It should be noted that these practices were not part of the earlier project where issues like misplaced steel, damaged steel, untraceable steel elements caused project delays with no centralised tracking system. Critical feedback from the site was often not recorded or acted upon, resulting in a delay in the erection of steel towers. However, in the current project, the intervention introduced to create a new embedded design resulted in the client's acceptance of the tower assembly following joint final inspection without any major rework. The impact of these interventions is discussed in the next section. It must be noted that all these activities for improving the embedded design cost time and money and is part of the cost of quality. As to whether there should be a trade-off between the cost of quality and the benefits does not seem to be of importance for risky cells; a feature of the embedded design that needs further investigation.

6. Results

Three interventions were considered as noted in Section 5 above. The number of NCRs raised before and after the interventions on the three cells are shown in Table 2. The issues surrounding the NCRs, the reasons for when the interventions took place, and the impact of these interventions are described next.

6.1 Results of Intervention 1: Transient cell cycle arrest (TCA) of excavation cell

The intervention on the excavation cell was to induce a TCA and stopping all activities because of the five NCRs recorded for excavation of 20 foundation boreholes. Following the intervention, the number of NCRs dropped to two for the remaining 508 excavated boreholes. Perhaps, the process could have been stopped earlier rather than at five NCRs. This reflection raises the issue of a threshold value of for inducing a TCA to make time to fix problems while the process is in a state of rest.

Table 2: Number of NCRs before and after intervention (all with rework)

Cells	Excavations for tower foundations	Concrete Supply	Tower Steel Erection
Interventions	Intervention 1: Transient state of rest	Intervention 2: Concrete supply cell readiness for production	Intervention 3: Embedded design for steelwork
No. of NCRs **before** intervention	5	N/A	N/A
No. of NCRs **after** intervention	2	0	2

The first author joined the project only after the start of the excavation cell, and therefore in this the opportunity for doing so was lost. However, the question as to a suitable threshold level remains. In this project, having stopped the process and identified solutions to the problem through a collaborative approach, permission was granted to re-start the cycle. Two more NCRs were issued, but the process was not stopped. One NCR was related to oversized holes (of bored piles) due to equipment malfunction, and the other was related to excavating a hole in the wrong location. This observation raises the question as to why a transient state of rest was not considered. Is it because of the good quality run of the process following the first state of rest and the cost benefit of stopping the process the second time is not favourable? Given the type of issue, it is likely that the nature of NCR has an influence on the induction of a TCA because one of the NCRs was due to an equipment failure. This observation leads to consider whether the cause of NCRs could be a significant contributing factor for the induction of TCA.

The second NCR following the intervention occurred a couple of days before the scheduled planned completion of the excavation cell i.e. the excavation was nearing completion within next two days, but no TCA was raised. The reason for this could be the small quantum of work left. In other words, it seems that lesser the amount of work to completion, lower the need for a TCA. However, further questions may be raised: Does the cell proliferation deteriorate when nearing completion indicating probably a lack of control? Or, are there activities outside of the control mechanism? Such deviations are not observed in the cell control mechanism; perhaps, a feature of the embedded design should be (see 6.3) to ensure that the processes for quality management are conducted with zest throughout without any indifference or lethargy.

Considering the importance of NCRs for determining the threshold, the current practice classifies NCRs as Class I, II or III depending on the cost and potential impact (Class I rework costs greater than \$100,000; Class II from \$20,000 to \$100,000; and Class III less than \$20,000). Any NCR with a Class I classification is investigated with a report submitted to higher management. However, this may result in the bulk of NCRs of class II and III escaping scrutiny. Clearly, the BCT approach is different and more stringent with a stoppage at each NCR rather than a threshold value of NCRs or the class of NCR. Interestingly, in this project, all the causes that lead to repeated NCRs were not the same and of class III. It seems that there is a need to investigate further as when a process should be subjected to a TCA.

6.2 Results of Intervention 2: Concrete supply cell readiness for production

This intervention on the concrete supply cell included confirming the readiness of the cell to participate in cell propagation, but it was necessary to check whether the plant was ready to deliver the desired quality. A hybrid audit checklist was prepared to check the preparedness of the plant and the system capability based on NRMCA guidelines and standard quality system requirements. An extensive audit of the facility was conducted to evaluate the readiness of the cell with the cell in *temporary rest* (i.e. not supplying concrete to the project unless observed as suitable to do so) similar to what BCT does regarding the readiness of the cell to participate in the cell cycle. This approach has resulted in correctly delivering the concrete and zero defect on the concrete supply for the project somewhat similar to checking a prototype cell's readiness for propagation. Accordingly, readiness checks can be classed as a feature of the embedded design as noted earlier.

6.3 Results of Intervention 3: Embedded design for steelwork

The interventions described in Section 5 have resulted in a relatively lower number of non-conformances requiring rework compared with a similar project completed in 2015. However, there were two NCRs. These NCRs were connected with two towers which were erected with an unacceptable gap between steel members and required partial disassembly of the tower to fix the issue. The question arises as to why this defects occurred despite ensuring the integrity of the embedded design? It is likely the inspection system missed the defects, and the ground team continued the erection with defective steel despite specific instructions not to do so (as noted before). Could the application of a TCA at the first NCR avoid this? The small number of NCRs recorded, perhaps did not warrant the need to put the cell in rest (unlike the excavation cell, based on intervention 1, discussed above). It appears that there could be a different threshold of NCRs for inducing such transient states of rest. These are decisions that need to be made to have an embedded design that is perfect.

The embedded design for the steel erection process did not include a TCA to fix the problem. However, the closest it came to doing this was by recording the NCRs and fixing the problem (of the problematic tower), thus providing a break in activity for the affected cell than a TCA for the whole cell (erection of all towers). The fact that a second NCR occurred suggests the embedded design was not flawless. However, the fact there were only two NCRs which was much less than in a similar project completed in 2015, suggests that features of the embedded design of the project under evaluation could have played a role in reducing quality problems. Perhaps, had a TCA been raised on the first time it occurred, the second NCR could have been avoided raising the question whether a TCA should be initiated at the first NCR - an issue that needs further investigation.

7. Conclusions

This study explored three features of BCT and BCCM taking a metaphorical approach to developing new insights for managing quality. These three features were: transient cell cycle arrest (TAC), readiness checks, and embedded design. Many cells can be identified for the application of the above features. However, only the most critical cells (i.e. core activities with a high potential for problems) were considered for trialling these concepts. Perhaps, this could be considered as a feature of the embedded design for the overall project.

The concept of inducing a transient state of rest is an entirely a new approach to construction quality management. Triggered by NCRs (with rework), it arrests the growth of defective cells. The senior management team has confirmed the usefulness of this practice as noted before. As to whether the arrest should be triggered by NCRs (or in any other ways) and whether just one NCR or a few or through a threshold value of NCRs is a matter that needs further investigation. The current system of classifying NCRs based mainly on re-work costs need to be reviewed too. Additionally, the need for a transient state of rest may depend on whether the NCR occurs at an early stage or later or close to the finish may have an impact. Additionally, whether the state of arrest should be limited to just the related activity of the defective cell only or for the full cell needs further investigation. Furthermore, as to how this concept could be introduced into quality plans and activity method statements may need investigation too. In essence, this is about understanding how to incorporate the feature of TCA in an embedded design taking into account of costs and benefits.

The embedded design if implemented well maintaining its integrity is likely to lead to positive quality outcomes. Some of the features of the embedded design that this study has identified in addition to the

TCA are: prototyping prior to cell propagation, lessons learnt imprints, cell readiness checks, constant surveillance mechanisms, feedback and feedforward loops, strict compliance with cell control mechanisms and product traceability systems. As the number of NCRs were very much less when compared to a similar project, it is conceivable that these features may have contributed towards keeping quality problems low, but the goal would be to have zero NCRs through further improvement of the embedded design.

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