Using the System Dynamics Methodology to Model the Competitive Index of Firms in the UK Construction Sector

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Abstract: In addition to assisting with the sense making of the complex interrelationships identified to exist between the external issues addressed in Goodier et al, 2006, system dynamics is also helping to interpret the findings from classical literature and firm case studies that have been undertaken into construction sector evolutionary pathways. These pathways have been structured using an adapted version of Teece's Dynamic Capabilities framework.

This populated framework forms the basis for the development of a system dynamics model of competitiveness. The dynamic activity in the model is driven by a performance metric – a competitive index. This paper presents the model development focusing on contractual competitiveness and the variables that impact on this during contract delivery. Feedback mechanisms are employed in the model to dynamically impact performance variables associated with the delivery process, thus updating the competitive index. It is envisaged that the competitive index may be applied to individual firms, thus providing construction suppliers and procurers with a dynamic indicator of a firm's delivery capacity and competitiveness.

Keywords: Competitiveness, Construction, Dynamic Capabilities, System Dynamics.

1. Introduction

This paper is based on continuing research at the University of Salford for the collaborative research project, between the universities of Loughborough, Reading and Salford. The research is centred on 'sustained competitiveness in the UK construction sector', with a number of particular objectives for each university. The primary research aim is to engage industry in the development and implementation of an integrated strategy in support of sustained, innovation-based competitiveness. This will be achieved by exploring and verifying possible economic, social and environmental future trends (Loughborough University), understanding the current structure of the UK construction sector (Reading University) and exploring their system interconnectivity using the mathematical feedback modelling methodology known as 'system dynamics' (Fleming et al, 2006). It is hoped that this collaboration will engage industry in an informed debate to help define a programme of action for individual or groups of firms, as well as providing strategic guidance for policy makers, culminating in a ten-year research agenda.

The University of Salford is using the system dynamics (SD) methodology to help understand the UK construction sector. This will potentially give insights into how firms (or types of firm) can use pivotal high-leverage variables to achieve sustained competitiveness. This is achieved by constructing a series of models, from a variety of theoretical perspectives, which convert a firm's characteristics into a competitive index (CI). This metric is then used to decide which firms in the construction sector are most competitive, and correspondingly win more of the available contracts.

The dynamic capabilities perspective is a firm-specific analysis. It focuses on the extent to which firms are able to re-configure their resources and re-modify routines in order to remain competitive in changing environments. Its framework consisting of three key elements – managerial processes, asset positions, and path dependencies – provides an intrinsic view of how competitiveness is operationalised and sustained inside firms. In summary, it is argued that the competitiveness of construction firms relies on two key qualities. First, the capacity to understand and identify the competitive forces in play and how they change over time; second, the capabilities to re-configure resources and re-modify routines to interact with their changing business environment.

The SD models run over a period of 20 years which allows a greater appreciation and understanding between causes and possible effects over the long-term, rather than just the immediate implications. Another notable SD model on competitive behaviour of firms in the construction industry is *A Dynamic Competition Model for Construction* (Kim, 2006), though this paper looks more into bidding behaviour and market changes. These insights will provide a greater understanding of the dynamic behaviour of the firm and its environment and thus enable improved decision making to be undertaken with regards to all aspects of procurement activity as addressed in Goodier et al (2006). The SD models therefore need to take possible future developments in the UK construction sector into account.

2. Dynamic Capabilities Framework

When attempting to understand how construction firms become and remain competitive, it is important to understand the changing context within which they operate. The UK construction industry has been influenced by a number of factors in recent decades: 'economic and industrial factors, government policy, social and technological changes' as well as 'external influences and changes which have been brought about by the industry itself'(Hillebrandt et al, 1995). Therefore, for a firm to remain competitive it needs to evolve in conjunction with the broader changing environment. To understand these dynamics of change the University of Reading has been engaging with medium-sized regional contractors, companies large enough to engage in some degree of strategising, to create detailed case-studies using an adapted version of Teece's 'dynamic capabilities framework' (DCF).

There are a number of dynamic capabilities frameworks, however, the Reading University research team have embraced the approach proposed by Teece (1997) as a broad view on the competitive strategy of firms. Teece and Pisano (1994) wrote that the first term 'dynamic' refers to 'the shifting character of the environment' whilst the second term 'capabilities' emphasises the ability of the firm to 'adapt, integrate and reconfigure internal and external organisational skills, resources, and functional competences' to create or sustain competitive advantage. Other perspectives, such as the competitive forces framework (Porter, 1980), fail to provide an intrinsic view of how firms adapt to their changing environment. The three key factors of a firm's dynamic capability are its 'resources', the way in which these are assembled and organised to perform activities in the form of 'routines', and the distinct capabilities that enable a firm to conduct its core business.

Building upon these three key components of dynamic capabilities an analytical framework for understanding the competitiveness of UK construction firms is proposed. The 'asset position' of a firm is examined in greater detail, examples would be: technological assets (e.g. the utilisation of specialised construction technologies provided by sub-contractors or manufacturers); complementary assets (e.g. the investment in computer equipment and trainings for the development of bespoke project management software); reputational assets (e.g. a good track record, a leading market position, an award for excellent performance, or a Kitemark for achieving certain standards); financial assets (e.g. owning properties and raising cash from external markets); structural assets (e.g. a flexible organisational structure and a vertical integration with sub-contractors and suppliers); institutional assets (e.g. the pre-qualification systems or procurement rules); and market assets (e.g. special types of construction works or contracting services).

The 'managerial and organisational processes' of a firm refer to the way things are done through a firm's routines of current practice and learning, and is a direct factor on a firm's competitive advantage. These processes include: coordination and integration (e.g. the coordination between delivery teams on site and off-site management teams, and the integration with other firms by strategic alliance); learning (e.g. learning new building technologies, project delivery improvements, and market changes); and reconfiguration and transformation (e.g. the responses to a client's new procurement method, the government's new policies, or emergent markets).

In addition, since a construction firm's competitiveness is conditioned by its historical path development, each firms history is profiled to identify potential strategies of benefit, such as the recognition and development of market opportunities (e.g. new types of contracts or works) or returns on a firm's previous investments on its capacities and routines (e.g. specialised skill trades and production processes).

3. Basis of Model Development

The primary purpose of the dynamic capabilities framework is to assert which factors have enabled a firm to remain competitive. The case studies undertaken by the Reading University research team have highlighted the complexity of the UK construction industry and the difficulty of decision making for individual firms in a complex world of rapid change. Whilst there are some characteristics specific to an individual firms, such as location and specialisation, which have enabled them to gain 'economic rents' (Teece, 1997) from the UK construction industry, there are many aspects common to all construction firms across the country, such as capital position and supplier relations, which create a competitive advantage. These factors identified are of primary interest in the construction of a model which will analyse the cause-and-effect behaviour on a firm's competitiveness by elucidating system relationships and interactions, capturing feedback processes and resultant system behaviour using mathematical modelling. It is argued that the competitiveness of construction firms relies on two key qualities. First, the capacity to understand and identify the competitive forces in play and how they change over time; second, the capabilities to re-configure resources and re-modify routines to interact with their changing business environment. With the use of system dynamics models to expose implicit assumptions and potential system behaviour arising from a range of different scenarios, each model may provide a useful descriptive and potential normative theory on competitive strategy.

It was felt that there are synergies between the adapted Teece framework and SD method. SD considers the causal effects of assets upon the firm in the same way that the adapted Teece framework highlights those assets needed for a firm to be competitive. Another reason for using SD is that it examines the effects that managerial decisions have upon the system. In addition SD considers resource flows including capital, labour, information, materials and energy. This enables SD to explore complex systems; the construction industry being one.

4. The Competitive Index

In order to inform which dimensions of firm-specific capabilities can be sources of competitive advantage, a composite measure of competitiveness is needed in this work and is referred to as a firm's 'competitive index' (CI). It is supposed that a total of '*i*' possible resources make up the competitive index, these are known as 'competitive factors' (CF). Each competitive factor is weighted in accordance to their relative significance on a firm's competitiveness, the sum of these weights equating to 1. The impact of the current state of the resource is rated in the competitive factor also on a [0, 1] scale. An overall competitive index is then computed by taking the product of each competitive factor CF_i with its corresponding weighting W_i and summing each overall resource *i*, which contributes to the competitive index, see equation 1.

$$CI = \sum_i CF_i . W_i \qquad (1)$$

where $\sum_i W_i = 1$.

By this measure then a firm with a CI equal to 0 is the least competitive possible and a firm with a CI equal to 1 is the most competitive possible. Each firm can have a CI of any value in the [0,1] range.

5. Setting the Model Boundary

The first step in the system dynamics modelling process is to define the boundaries (Sterman, 2000). There are a number of methods and tools available for this task: here a 'high-level map' was chosen for the initial starting point (figure 1) before a boundary chart was drawn.

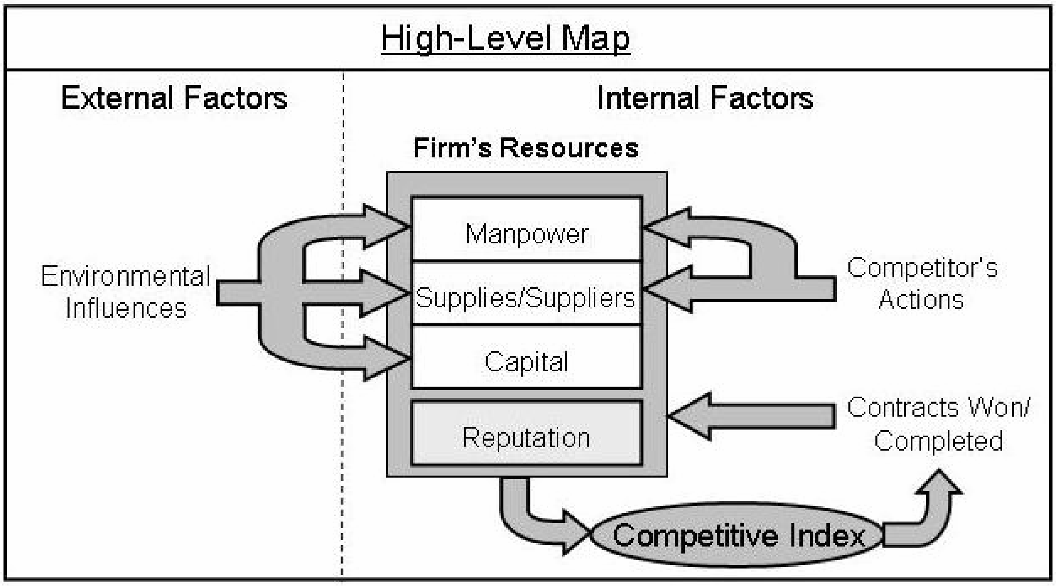

Fig. 1. High-Level Map of How Resources Relate to the CI and are Externally Impacted On

The high-level map is a visual aid that diagrammatically shows the major variables that will be present in the model as well as some of the influences or resource flows, in the system. The high-level map takes a strategic view of the system, with the details of influences and actions being described elsewhere to keep the diagram clear and easy to understand. The objective of this map is to show how a firm's resources impact upon their competitive index and how these resources can be influenced by factors that are both internal and external to the construction industry.

To complement the high-level map a 'Three E's Table' was created, which has been partly reproduced in table 1. A Three E's Table categorises the variables present in the model, with regard to their level of involvement. The Three E's table is an adaptation of a boundary model chart that has previously been used in the construction of system dynamics models regarding policy (Groesser, 2006). The three headings relate to the variables and are endogenous, exogenous and excluded. Endogenous variables relate to the assets seen in the adapted dynamic capabilities framework. When using SD, endogenous means that the behaviour is self generating in the model, through a series of feedback loops, where as exogenous variables feed into the model but cannot be influenced by changes in the model. Two variables that are thought to have relatively inelastic short-term affect on the construction industry are supply and labour costs, (Rawlinson, 1997; Akintoye, 1998). Both of these are seen as exogenous, rather then excluded, variables here as the model runs for a long time period. Excluded variables are variables not present in the model.

Table 1 – Current Proposed Boundary Table for Competitive Index Model

Endogenous	*Exogenous*	*Excluded*
Firm's manpower	Labour market	Weather Patterns
Firm's capital	UK economy	Raw Material Limits
Firm's reputation	Suppliers	
Contracts in the market	Supply Costs	
Capacity of firm's WIP	Contracts in the market	
Delays in Starting Work	Labour Costs	
Delays in Completing Work		
Effects of Delays		

6. Constructing System Dynamics Models

A short review of the development of this SD model is now explained. In the development of the model a singular variable is modelled, before adding further variables. This is to facilitate the understanding of how this variable affects the firm's competitive index over the 20 year model cycle. In this paper the number of contracts won by a firm, given its CI, has been modelled.

For the purposes of this model cycle, the following assumptions were made in terms of the basic flow of a contract:

1. A number of new contracts are released into the market (entering the system).
2. Contracts are won by competing firms, with the allocated proportions being dependent on their respective CI.
3. The contracts are completed, when contractual requirements have been satisfied (leaving the system).

The above steps are known as 'flows' due to each step being over a time period, e.g. the number of contracts completed per year.

6.1 The Stock and Flow Diagram Layout

The system dynamics method can use a number of visual aids, including tree diagrams, influence diagrams and stock and flow diagrams. In this paper stock and flow diagrams are presented, as they simply represent structure and produce graphical and tabular output. This section helps to briefly explain the main characteristics of stock and flow diagrams.

As discussed above, there are a number of resource flows present in the model and it is these flows that drive the model. Flows enter into and exit from 'stocks' apart from those flows that enter or exit the system. The 'clouds' show the points at which flows enter and exit the system. Furthermore, variables can be fed into the system as auxiliary variables. Figure 2 shows a 'stock and flow' diagram explaining each of the different elements described above.

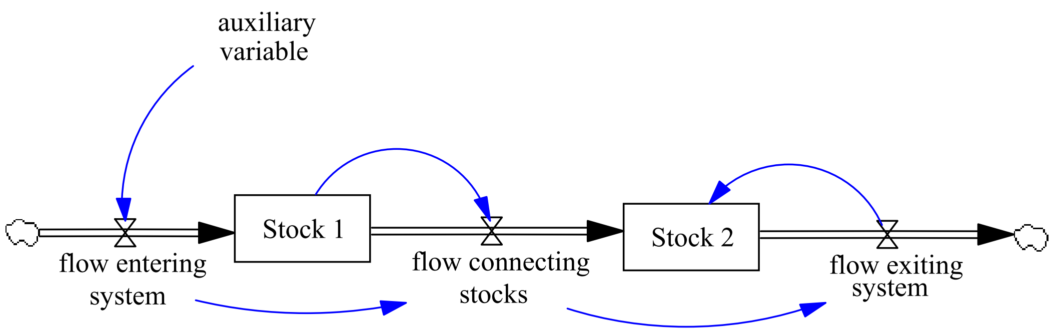

Fig. 2. Stock and Flow Diagram Layout

6.2 Modelling Affects of Contracts Won by a Firm

The model was built from the three flows, contracts released, contracts won and contracts completed, (figure 3) and incorporated the relevant stocks and auxiliary variables.

There are two aspects of this model that need to be stated. The first is that the CI is an auxiliary variable without being affected by internal or external influences, and the second is that this is a 'sub-scripted model' with three firms (labelled A, B and C) running concurrently in the same model.

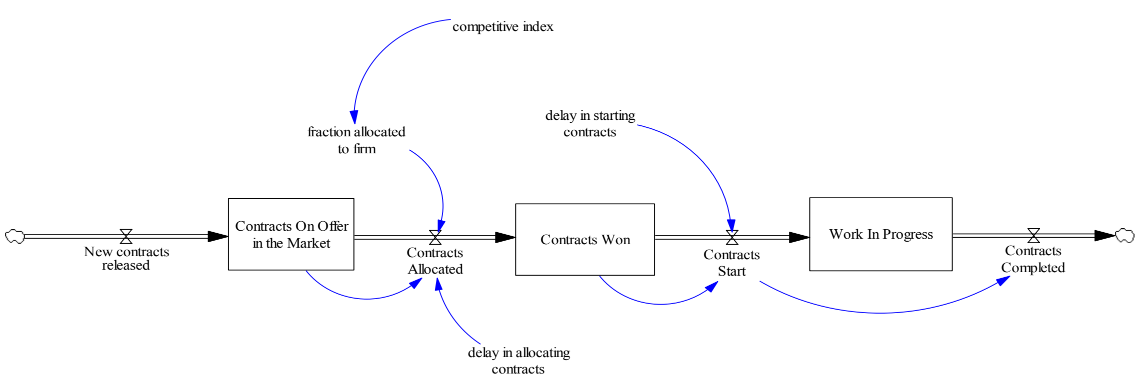

Fig. 3. Stock and Flow Diagram of Contracts Model without Feedback

The model runs the system in a state of equilibrium, without changes to any variables. By incorporating feedback structure, non-linear behaviour is created. It is the non-linearity and feedback attributes that makes system dynamics such a powerful modelling tool. This was achieved by incorporating a work-in-progress capacity limit, with firms being penalised (with a reduction in the CI) if they breached this (figure 4). The penalty is justified because as the firm breaches its capacity limit, it will fall behind and be late in completing contracts.

Any resulting drop in CI will give them a smaller share of the contracts on offer in the market. This means that their WIP will fall and the firm will be able to reduce or remove the delay in completing the contract. The contract reduction will lead to the firm's CI increasing to its original level.

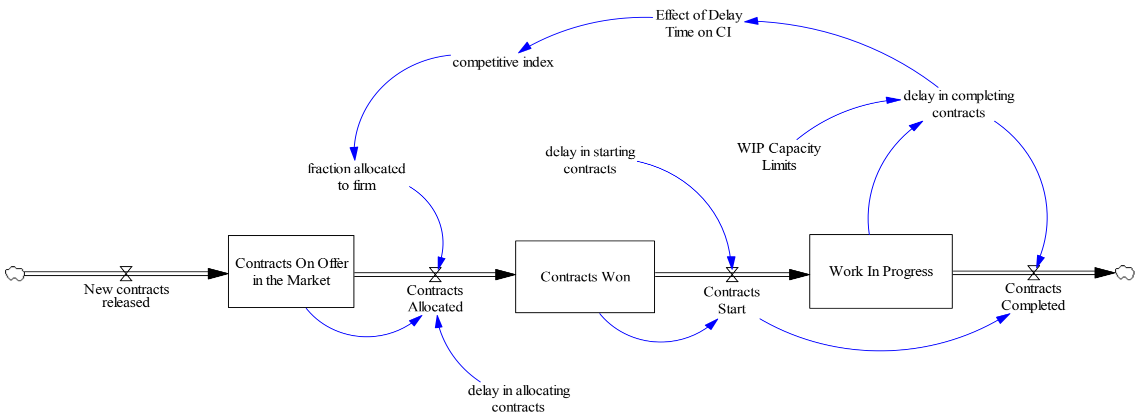

Figure 4 – Stock and Flow Diagram of Contracts Model with Feedback

As an example of how the model reacts, firm B's competitive index was arbitrary increased at time t=5 years. The increase in firm B's CI led to a greater fraction of contracts being allocated to firm B, which in turn increased firm B's work in progress (WIP). Once the WIP, of firm B, exceeded their 'WIP capacity limit' delays in completing contracts appeared, which led to a decrease in firm B's CI.

The decrease in firm B's CI led to firm B being allocated less contracts and therefore reducing their WIP and eventually omitting delays in completing contracts. By omitting delays firm B's CI increases and the cycle repeats. The Vensim® software used in the construction of the system dynamics models can output graphs of the model variables. Figure 5 shows the CI for all three firms, however firm A and firm C have identical plots and therefore only one plotline is visible for both of firms A and C.

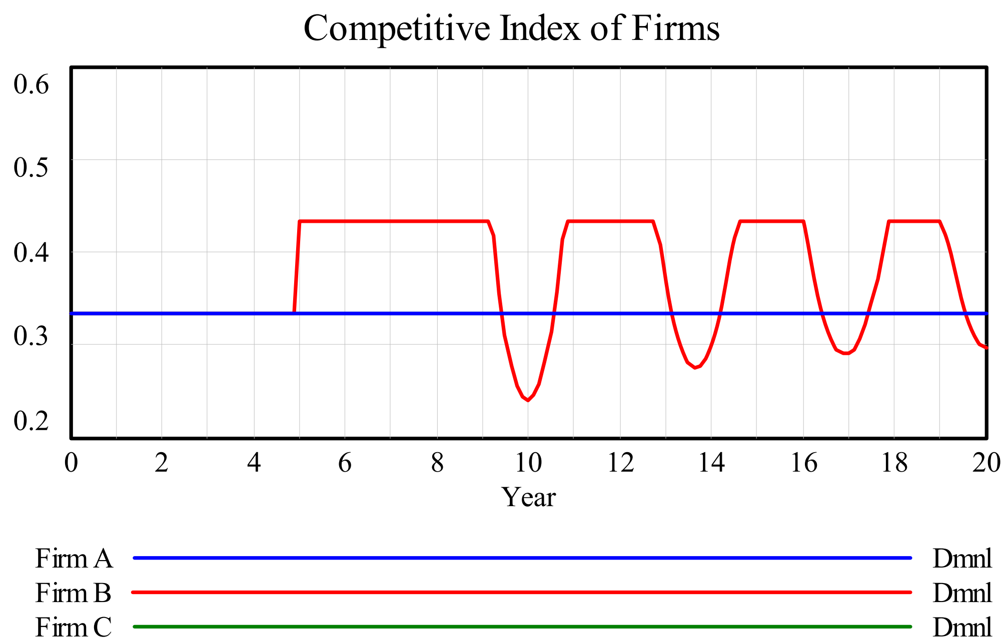

Fig. 5. CI of All Firms after Increase in Firms B's CI

The decreasing oscillations in the graph are due to the balancing nature of the system. By increasing the number of years the model is run for a repetitive pattern will emerge in the oscillations, this will be at the approximate length of a business cycle (4-6 years). It must be noted that at this stage of the research the contracts in the market variable has been used. Other endogenous, exogenous and excluded variables will be incorporated as the research progresses.

7. Future Model Developments

In order to build models that can better simulate the UK economy, as well as gain an increased understanding of how firms react to changes and how firms interact with each other, a number of model developments are required. These developments involve building the suppliers, supplies, capital (of the firms), workforce and external influences into the models. These future developments will continue to be based around the dynamic capabilities framework, which helps in the understanding of how a firm's assets relate to their competitiveness.

8. Using the Competitive Index for Procurement Purposes

The ongoing research described in this paper is developing a competitive index that uses System Dynamics to convert a firm's characteristics into a performance metric called a competitive index. It is suggested that firms within the UK construction sector may subscribe to this competitive index metric as a dynamic indicator of their competitiveness. The metric could be used as a tool to assess the competitive performance of a department or division within a larger organisation. Alternatively it could be used to offer an indication of a firm's competitive performance in the wider marketplace, in this case the UK construction sector. This indication may be of use to other organisations within the firm's transactional boundary such as members of its supply chain or those procuring its services or simply stakeholders who are impacted by the firm's actions. Whether the metric is one that is self regulated by organisations within the industry or is regulated by a third party is a question for future debate, once the metric is further developed.

9. Conclusions

This paper has presented how an adapted version of Teece's 'dynamic capabilities framework' (DCF) is being used by the University of Reading as a lens to potentially understand how firms evolve in conjunction with the broader changing environment. This work is serving to inform research that is being undertaken at Salford University that is using the modelling technique called system dynamics. It is felt that the technique is appropriate for modelling construction as it is particularly adept at modelling complex entities. The technique is capable of modelling and simulating trends and structural factors for a range of diverse scenarios. These scenarios enable insights to be gained into the construction industry's behaviour to enable key policy makers to review existing policies and determine appropriate policies for future implementation. To date, models have been developed that are informing the development of a performance metric called a competitive index. This metric will indicate how firms compare in terms of competitiveness within the UK construction sector. Further research will refine the model further. It is hoped that this paper will stimulate discussion and debate as to the potential applications this metric may have for the Construction Industry.

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