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Dynamic Modeling of Building Services Projects: A Simulation Model for Real-Life Hospital Project

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Abstract: All infrastructure projects are said to be inter-dependent, uncertain and labour-intensive in nature. There is no exception for building services sub sector. For a real time project such as 'The construction, extension and refurbishment of Employees' State Insurance Corporation (ESIC) Hospital at Tirupathy, India with total area of 45,000 square feet at an estimated cost of 1100 million rupees, a generic process model is developed to simulate the effect of set of identified variables on construction project. The 'Stocks and Flows' of dynamic model affords relevant insights to project managers, who apply this knowledge when designing better performance through more appropriate project planning. It is concluded from the model-based approach that building services works can be improved through specific better focussed managerial efforts, such as an increasing coordination effectiveness at the planning stage, clarifying prerequisite conditions prior to installations. Otherwise, pending works arising from work clashes can lead to knock-on effects resulting in productivity constraints and pressures, as well as more rework and demolition. Current study reveals that the model enables deep insight into various interdependent processes, their by improving construction performance levels, by addressing the dynamics of design errors and defective works, and recovering delayed schedule.

Key words: Construction Projects, Construction Project Performance, Dynamic Model Structure, Endogenous Variables, Exogenous Variables

I. Introduction

The construction industry is next to agriculture sector, which provides more employability in India. However, this industry is often been criticized in many review reports, for the excessive use of manpower and relative poor performance in the operation and product quality. This is significant in the building services sub-sector of the construction industry, where coordination among many specialist contractors needed.

In construction industry, it is very difficult for any organization to plan strategically and remain competitive in execution of different types of infrastructure projects. An investigation has been carried out to understand the historical evaluation and changing face of the construction sector and the dynamic capabilities needed for an organization to execution of various infra structure projects in secure a more sustainable manner.

System dynamics has become very useful methodology for modeling and simulating the quantitative changes and dynamic nature of the projects. This method can be widely useful in construction/infrastructure industry by choosing appropriate Casual-Loop Diagram and Stock-Flows Diagram for assessing impacts of design errors, housing supply and demand, impact of urban policies on urban development, and construction competitiveness etc.

In building projects the existence of reworks and non-value adding variations ultimate impact on installation processes. In addition to that, poor allocation of work sequence and inadequate workspace may be cause of more services clashes. Above and all pending works from uncertain works suddenly accumulate also impacts seriously, resulting in lower productivity and more reworks in building projects. The shortcomings encountered in the inherently dynamic field of project management are typically treated in a static manner. Hence, in order avoid aforesaid incidents, system dynamics modelling has been recommended for dealing with the dynamic complexity of construction projects.

II. Literature Review

Sterman [10] and Lynesis et al. [9] came across short coming in the dynamic field of project management, since variables are treated as static in their studies. Sterman et al. [10] reported dynamic behaviours understanding in project management will explore full potential of operational improvement. Rodrigues et al. [11] and Hao et al. [7] suggested system dynamic modelling approach for dealing with dynamic building services projects. Wan et al. [6] stated from their findings to overhaul the current system of managing the building services projects. Hawkins [8] reported that a complete review on constructability of specialist contractors improve construction efficiency. Sammy et al. [5] developed a generic dynamic model for building services projects and applied over two quite different projects in Honkong. Sang won et al. [1] applied system dynamic model for quantitative estimation of design errors and it interns leads to develop proper mechanism to enhance

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project performance. Min-Ji Kwoun et al. [2] applied system dynamic model to find dynamic relationship between hosing supply and demand, and investment policy. Mooseo Park et al. [3] developed system dynamic model has a potential to assist decision makers in judging the impacts of various self-sufficient urban development policies. Norman Gilkinson [4] reported dry run of strategy through simulated scenarios helps to lessen unexpected behaviour and offers insights about how endogeneous behaviour can shape the upcoming projects. The above literature review revealed that the dynamic model enabled complete understanding of the process and also helped in improving performance levels.

This paper presents a generic dynamic model structure firstly by identifying key endogenous and exogenous variables. Using the above model a case study carried out for 1100 million rupees project that involved "Construction, Extension and Refurbishment ESIC Hospital, Tirupathy, India" to know construction performance. The new hospital building consists of basement and ground floor with five floors over it with a total plinth area of about 45,000 square feet.

III. Formulation of System Dynamics Generic Model Structure

A. Variables of model boundary

In the current ongoing study at the construction of ESIC hospital site Tirupathy, it was found that coordination across different specialist contractors, who are working concurrently and competing for site resources was quite challenging, particularly on the constraint of tightened construction program. Meanwhile, the upstream design changes and design errors during execution, in particular of ductwork or pipe work installations, reinforcement fabrication, cantering of beams and slabs, and change in the brick work drawings led to invariable duplication of works, demolition and/or reworks. On the other hand, the lack of coordinated planning with subcontractors for material handling and shuttering led to arguments, waiting, and interference with other trades, and even damage to materials and equipment. Very often, if the fabrication errors or mistakes are not captured early enough by experienced site supervisors, this might contribute to potential defective works or even reworks. The lack of knowledge of other building services trades might also add to fabrication errors and potential service clashes in particular within complex routing assemblies, which could otherwise have been anticipated and minimized, if not avoided.

A system dynamics modelling approach was adopted for dealing the dynamic complexity in construction projects. This approach is powerful in providing analytic solutions for both complex and nonlinear systems. Most projects are constrained by traditional budgeting, which bears little relation to production shortcomings. To overcome this constraint, the impacts of various dynamics behaviours and possible improvement strategies on construction performance were analyzed. Variables of the model boundary are required for the formulation of system dynamics generic model structure. Key variables were identified from site conditions and are mainly classified into endogenous and exogenous components in terms of some what large model boundary as given in Table I.

B. Description of generic model structure

The dynamic behaviour of the cause and effect relationship and underlying interdependencies between the less tangible identified variables from the site was analyzed for constructing the skeleton of a generic system dynamics model structure. This step involves identification of stock and flow diagrams where 'stock' represents accumulated quantities whereas 'flow' controls the changing rate of quantity going into/out of stock. In order to ensure all stocks and flows are mathematically and dimensionally consistent with realistic meanings, 'Planned Works', 'Actual Works', 'Pending Works', 'Defective Works', 'Demolition Works', 'Works Awaiting Inspection' and 'Works Released' should be taken as stocks of the model structure.

All the flows should be modelled on an arbitrary scale of 0%–100% instead of numerous complex and uncertain formulas for simulation at this stage. An arbitrary scale of 50% is the average of this rating scale. And 80% or more indicates an outstanding performance in a particular variable in which all respective parties are well coordinated or individual factors are well performed, excluding the variables of 'design changes', 'design errors', 'over production of in-process works', 'service clashes/conflicting works' and 'fatigue'. For which 80% or more represents frequent or severe occurrence, adversely affecting the construction performance. Arising from the aforesaid approaches, a generic system dynamics model structure was proposed as shown in Figure I.

IV. Analysis of Generic Model Structure with Regards to ESIC Hospital Project

As shown in Figure I, the building services works are planned in a master program in the first stock, 'Planned Works'. Of course some variables such as work progress, architect or site instruction, readiness of upstream process, etc could drive whether and when the succeeding work can be planned in the master program. After the works in the 'Planned Works' stock are planned, works for execution are determined by the flow 'Work Availability'.

TABLE I
VARIABLES OF THE MODEL

Endogenous Variables	Exogenous Variables
▪ A1 Planned works	▪ F1 Coordination effectiveness
▪ A2 Work requisition	▪ F2 Sequence of specialist works
▪ A3 Work availability	▪ F3 Allocation/adequacy of resources
▪ A4 Actual works	▪ F4 Design changes
▪ A5 Client-directed changes	▪ F5 Design errors
▪ A6 Uncertain/conflicting works	▪ F6 Communication effectiveness
▪ A7 Pending works	▪ F7 Approval effectiveness of technical submissions
▪ A8 Work clarification	▪ F8 Effectiveness of issuing instructions
▪ A9 Error generation	▪ F9 Selection of suppliers/subcontractors
▪ A10 Defective works	▪ F10 Incoming materials/equipment
▪ A11 Discovered work need demolition	▪ F11 Protection of materials/equipment
▪ A12 Demolition works	▪ F12 Site storage for materials
▪ A13 Works requested for inspection	▪ F13 Site layout/condition
▪ A14 Defects needing demolition	▪ F14 Distribution and/or adequacy of work spaces
▪ A15 Works awaiting inspection	▪ F15 Overproduction of in-process works
▪ A16 Unsatisfactory works	▪ F16 Service clashes/conflicting works
▪ A17 Defect rectification	▪ F17 Fatigue
▪ A18 Discovered work need change	▪ F18 Workmanship
▪ A19 Work release	▪ F19 Relevant skill level/experience
▪ A20 Discovered hidden error	

The main idea behind this flow takes into account that specialist contractors always perform work concurrently and compete for on-site space, shared equipment and resources. Prerequisites such as work sequence, explanatory drawings, appropriate equipment and work stages should be well defined, planned and executed. Suppose in areas where a false ceiling is to be installed to conceal services, electrical wiring connection may not be able to commence in case there is not enough work space inside the plant room or on-site equipment such as working platforms are not provided for the site operatives. In this case for instance the flow has only 10% availability, the amount of planned works moving to 'Actual Works' would be constrained resulting in less than 10% working actually on site, in particular of concurrent ceiling works, ductworks, pipe works and conduit works within a confined area.

Demanding market needs and changing preference of developers or designers may trigger such project change through the flow of 'Client-Directed Change', as one of the specific factors of the generic model project disruptions may be caused by 'Client-Directed Change' causing productivity losses. In other words, some portion of actual works may be re-planned in the master program at the stock, 'Planned Works' was being physically executed on site. After works are executed on site at an 'Available Work Rate' that considers availability of incoming equipment/materials, workspace availability, skill level and experience, workmanship, etc., works done will await installation inspection at the stock 'Works Awaiting Inspection'. Some of the works which may need to be clarified could have been constrained by 'Creating Pending Works', the degree to which design uncertainties, service clashes, etc., are identified in the actual works. These works are accumulated in the stock of 'Pending Works' and they may be determined to be sent back to 'Actual Works' if the client representative or consultant engineer issues clear information/instruction to clarify the problems on hand through the rate of 'Resolving Pending Works'. As shown in Figure II, higher work intensity and inadequate work spaces cause more work clashes or conflicts when specialist contractors' work concurrently and this forms a reinforcing loop (R1) with more work clashes and/or conflicting works which lead to even more pending works.

Project Managers normally issue more 'Requests for Information/Instructions' for clarifying and resolving the increasing number of pending works to the consulting engineers through another reinforcing loop (R2) as shown in Figure II. As project milestones approach and even elapse, some trades may try to complete their segregated works to prevent being trapped in the critical path and being held responsible for the liquidated damages in case of any delay, but this may create more probable conflicts or clashes. This may also raise difficulties over the resolution of pending works as represented by a counteracting loop (R3) in Figure II. Fabrication errors usually occur depending on site storage conditions, skill relevant experience, workmanship, etc at the rate of 'Error Generation'. And hence some completed works are accumulated into the stock of 'Defective Works'. As the number of rectifications and re-inspections arising from defective works increases, the expected delays and/or losses because of the invariably tight work schedules in the construction of ESIC Hospital cause even more pressure on productivity expectations. The attempts of acceleration and/or outsourcing increase workloads under short-term pressure but reduce workmanship levels and induce fatigue in the longer term, resulting in a reinforcing loop (R2) in Figure III.

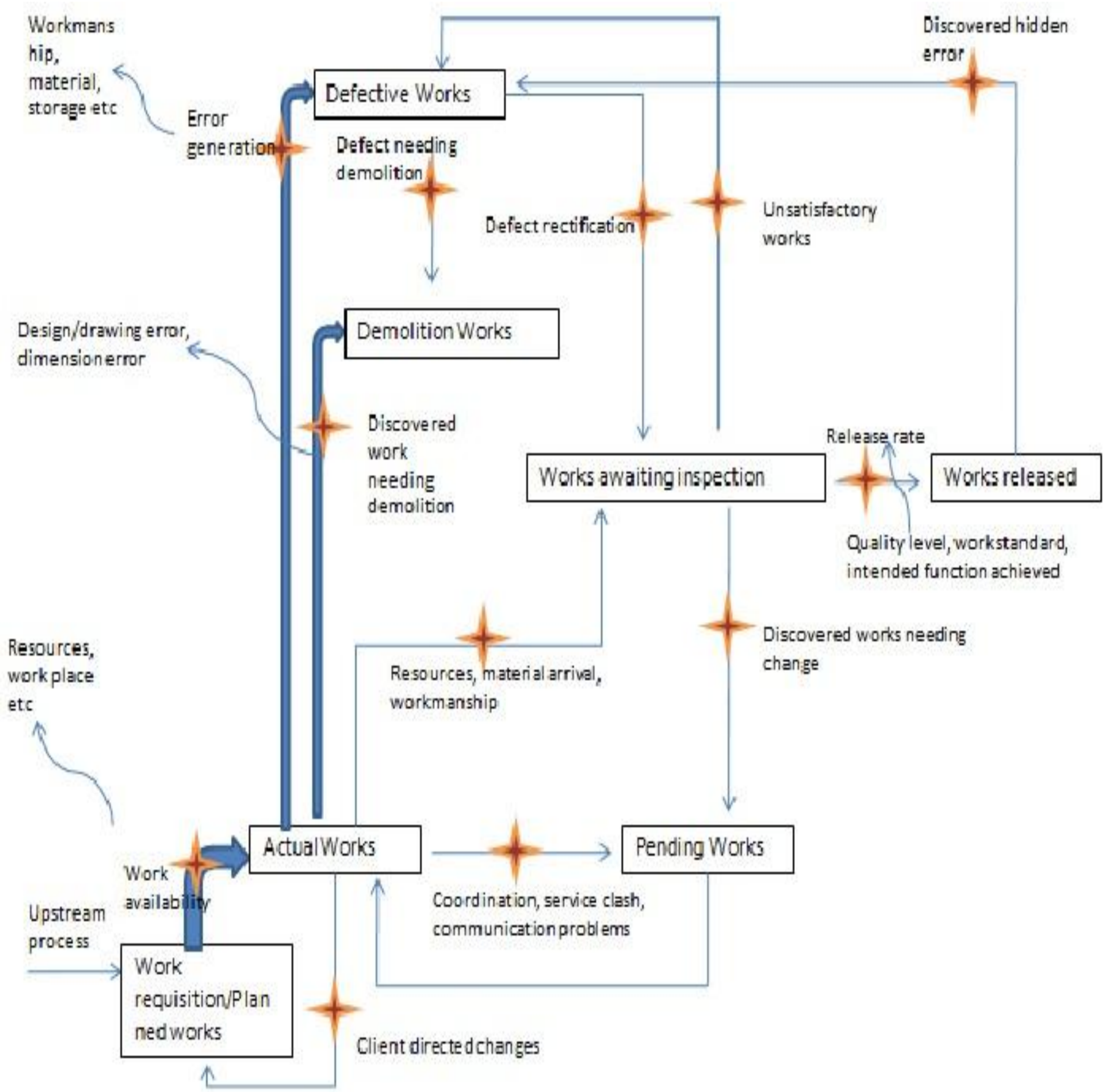

FIGURE I
GENERIC SYSTEM FOR DYNAMICS MODEL STRUCTURE

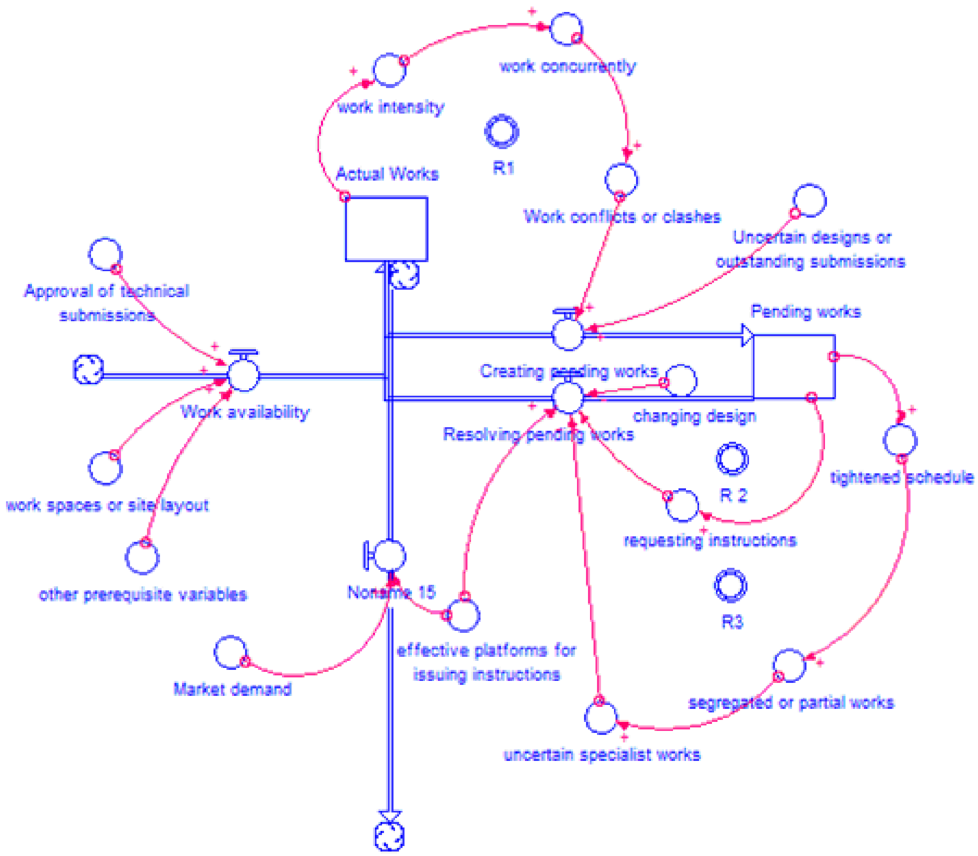

FIGURE II
CONCEPTUAL LOOP DIAGRAM-ACTUAL AND PENDING WORKS

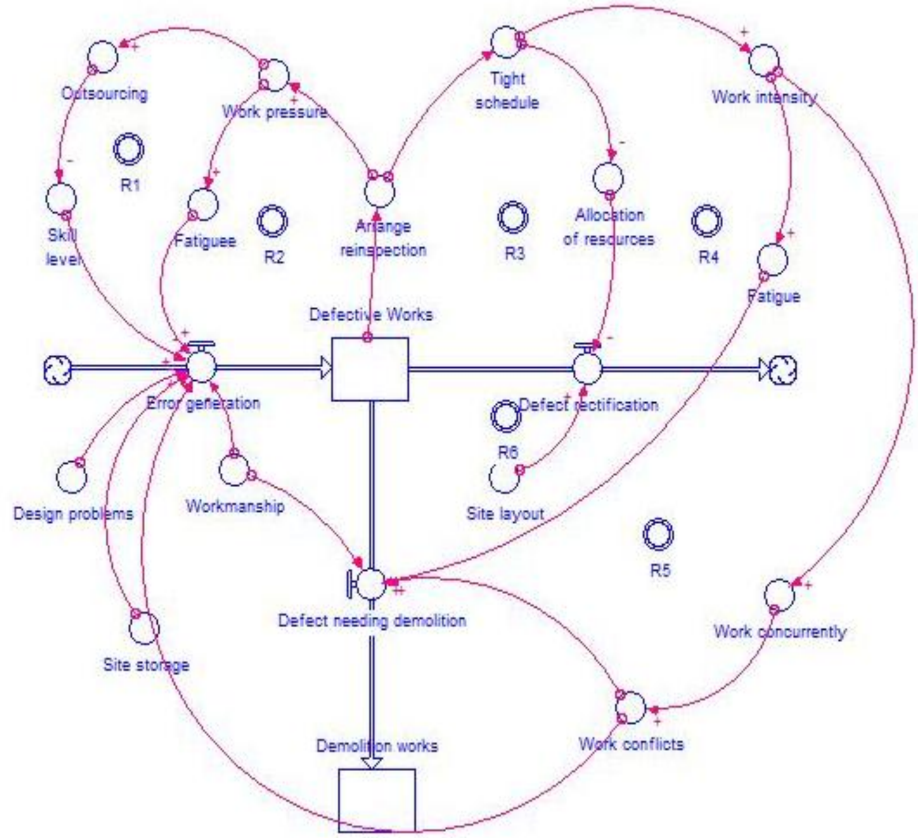

FIGURE III
CONCEPTUAL LOOP DIAGRAM – DEFECTIVE AND DEMOLITION WORKS

Incompetent and inexperienced workers may be employed to stimulate work progress but this may lead to more poorly coordinated works and work clashes as represented by another reinforcing loop (R1). Two options are available for the defective works. The works may either be rectified and returned to the stock of 'Works Awaiting

Inspection' again, or moved to the stock of 'Demolition Works' depending on the defect condition, workmanship, skill level/relevant experience, worker's fatigue, etc. If the defect needs much time and resources for rectification, the project manager may decide to demolish it right away. Even if some site operatives identify the problems and intend to rectify the defects, availability of resources and worker capacities may constrain their ability to communicate feedback among relevant trades or crews. Two counteracting loops (R3 and R4) may build up and this could lead to a decreasing rate of 'Defect Rectification'.

But some defects in building services works may not be able to be directly rectified. For instance, the plinth beam of the structure was cast after raising three floors of the structure due to poor communication at the site. Also, a defective concrete plinth will have to be demolished if the structural capacity is not able to bear the loads and ductwork respectively. Additionally, pipes, ducts, and the associated ancillaries may have to be demolished if the defective work is related to an incorrect size of supply duct connecting to grilles. Such 'Proneness' to defect rectification becomes one of the specific factors of the works. The flow of 'Defect Needing Demolition' is assumed to be further constrained by the scope of work in addition to defect condition, skill level/relevant experience, worker's fatigue, etc. This exacerbates the effect of 'Defect Needing Demolition' at a reinforcing loop (R6) in Figure III. Meanwhile, higher work intensity and inadequate workspaces can cause more work clashes and this becomes a reinforcing loop (R5) which leads to even more non-value-adding demolitions rather than rectifications.

In some cases, a portion of completed works flow to 'Demolition Works' through the degree of 'Discovered Work Needing Demolition' probably because of dilapidated/mismatched materials, services clashes, technical problems in dimensional tolerance. Particularly in ESIC Hospital construction site, where specialist contractors always struggle amidst tight and complex configurations within a tight schedule. If field conflicts and/or potential problems remain unresolved, the completed works are likely to interfere with one another and thus could result in non-value-adding demolition. Along with this model structure, a tri-flow structure is adopted to model the results of the stock of 'Works Awaiting Inspection'.

The completed works are monitored and inspected by the client's representatives or consulting engineers. Depending on the work quality, the works may be released to the stocks of 'Works Released', 'Defective Works' or 'Pending Works'. In principle, works achieving specified work standards, quality levels and intended functions are approved as 'Satisfied Works' and moved to the stock of 'Works Released', while others are disapproved and moved to the stock of 'Defective Works' for rectification. Productivity pressure and tight work schedule can also lower work quality since workers often attempt to achieve the target schedule by cutting corners. When overtime continues, workers become fatigued which possibly lowers work quality. However, some problems of design, service clash, tolerance, etc., that have not been discovered in work processes are now identified in the stock of 'Works Awaiting Inspection'. Once they are found, those works are moved to 'Pending Works' waiting clarification or change requests to be initiated by the contractor.

Sometimes, hidden errors may be identified at a later stage at the stock of 'Work Released' governed by a flow of discovered hidden error. With this, related works are sent to the stock of 'Defective Works', which needs rectification or demolition. When works are released to the downstream, they are supposed to manifest a precedent iteration relationship by affecting the downstream flow of 'Work Requisition'. The more upstream processes are delayed, the more often disruptions will happen in planning downstream works.

V. Conclusions

Present study has attempted to analyze the interrelationships of the various processes, by taking the lead to adopt the system dynamics modeling approach for building services project, i.e. 'Construction, Extension and Refurbishment of ESIC Hospital' at Tirupathy. The conclusions drawn from the above study is as follows:

- This site investigation enabled the identification of a number of endogenous and exogenous variables which influence flows among the carefully determined stocks in the '*Stock and Flow*' diagram of the system dynamics model.

- The stocks are identified as '*Planned Works*', '*Actual Works*', '*Pending Works*', '*Defective Works*', '*Demolition Works*', '*Works Awaiting Inspection*' and '*Works Released*' to reflect the practical scenario of a typical building services project.

- From the dynamic simulation model approach, many challenges faced by ESIC Hospital project, such as poor communication between consultant and contractor in clarifying design and drawing details, selection unprofessional contractors, lack of technical supervisors, employing unskilled labourers, use of inferior shuttering and building materials, and working of specialist contractor with amidst tight schedule, can be analyzed and find solution from careful analysis of interdependent processes.

- The construction of ESIC hospital could be improved with more focused managerial efforts, such as increasing coordination effectiveness at the planning stage, clarifying design decisions collaboratively for inter-dependent works and ameliorating important pre-requisite conditions prior to installations.

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