

A System Dynamics Approach for Reduction of Defects in Automotive Manufacturing Industry

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Abstract

The automotive industry is one of the biggest manufacturing sectors and represents an increasingly important strategic and catalytic role in the overall economy. It impacts directly on many important aspects, such as contribution to gross domestic product (GDP), employment, skills development, economic linkages, technology and innovation, and making significant contributions through taxes, and substantial foreign direct investment. Yet, defects are a manufacturing reality influencing this industry. The purpose of this paper is to show how the system dynamics methodology can be applied to reduce defects in the automotive manufacturing industry. System dynamics may improve understanding of manufacturing processes, as quality tools do not always allow the user to study and understand feedback from other factors, such as soft human issues, in the improvement of processes. Systems dynamics models are created from five stages: problem articulation, formulation of a dynamic hypothesis, formulation of a simulation model, testing of the model, and policy design and evaluation. The five steps of system dynamics modeling process are discussed into details and a causal loop diagram is developed using Stella software version 9.1.4. The study showed that system dynamics tools can be useful in capturing and understanding the dynamic complexity of defect creation and reduction process in automotive manufacturing industry.

Keywords

System dynamics, automotive manufacturing, defect reduction, modeling process.

1. Introduction

The automotive industry is one of the biggest manufacturing sectors and represents an increasingly important strategic and catalytic role in the overall economy. It impacts directly on many important aspects, such as contribution to gross domestic product (GDP), employment, skills development, economic linkages, technology and innovation, and making significant contributions through taxes, and substantial foreign direct investment (Lamprecht, 2018). Yet, defects are a manufacturing reality influencing this industry. To be viewed as competitive in the manufacturing industry, organisations must strive towards minimizing waste and thus increase their productivity (Liker, 2009). Defects can be defined as any characteristic of a product which hinders its usability for the purpose for which it was designed and manufactured. Quality tools such as, check sheets, cause and effect diagrams, Pareto charts and flow charts can be used for the day-to-day management of large automotive manufacturing plants, but these tools don't capture the dynamic complexity of defect creation.

The purpose of this paper is to show how the system dynamics methodology can be applied to reduce defects in the automotive manufacturing industry, the five steps of system dynamics modeling process are discussed into details. A system dynamics approach is a simulation method in solving real-world problems to describe relationships among variables in complex real systems. Systems dynamics models are created from five stages: problem articulation, formulation of a dynamic hypothesis, formulation of a simulation model, testing of the model, and policy design and evaluation (Sterman, 2000).

2. Literature review

2.1 Background on system dynamics and the modeling process

System dynamics (SD) was developed by Dr. Jay W. Forrester in the 1950s at Massachusetts Institute of Technology, and it has increasingly developed into a tool useful in the analysis of social, economic, physical, chemical, biological, and ecological systems (Sterman, 2000). It is a computer-aided approach to policy analysis and design used to analyse and solve complex problems with a focus on policy analysis and design through understanding the dynamic behavior of systems (Dung Ho et al., 2018). In system dynamics, several diagramming tools are used to capture the structure of systems, including causal loop diagrams and stock and flow maps. Casual Loop Diagrams (CLD) are used for representing the feedback structure of systems and the casual relationship among system variables and stock and flow diagrams for obtaining variables in mathematical equations (Sterman, 2000). “SD model development involves a number of iterative steps ranging from knowledge elicitation and qualitative modelling to simulation of alternative scenarios” (Derwisch & Lowe, 2015). Systems dynamics models are created from five stages: problem articulation, formulation of a dynamic hypothesis, formulation of a simulation model, testing of the model, and policy design and evaluation (Sterman, 2000). The five steps of the system dynamics modeling process will be discussed in detail in section 3.

2.2 Argument for using the system dynamics methodology in manufacturing

There has been a recent increase in the number of published studies using the system dynamics method to model manufacturing systems and supply chains for a variety of purposes (Haddad and Otayek, 2018). This is due to the realization by academics and practitioners that manufacturing systems are increasingly complex, and that process modeling and simulation are valuable tools to deal with complexity in a cost-effective way.

The following authors raised the importance of using System Dynamics in manufacturing.

- Manufacturing defects are best understood with the use of systems thinking and System Dynamics (SD) modeling, especially when the purpose is to identify the problem and its root cause (Haddad and Otayek, 2018).
- System Dynamics may improve understanding of manufacturing processes, as quality tools do not always allow the user to study and understand feedback from other factors, such as soft human issues, in the improvement of processes (Van Dyk and Pretorius, 2014).
- System Dynamics model does not only identify the causes and relates to their effects but also provide feedback. Thus, to understand the dynamic behaviours of manufacturing systems, tools such as system dynamics models are necessary. Application of system dynamics models in the analysis of manufacturing defects could be an effective tool to optimize process improvement initiatives more effectively and efficiently (Chowdhury et al., 2014).
- Alefari et al., (2018) states that System Dynamic is the most appropriate tool when building a model that can predict the impact and the relationships of all different factors affecting manufacturing processes.
- By understanding the behaviour of different factors in manufacturing processes, practitioners can formulate policies that have a sustained impact on the organisation (Duvvuru et al., 2012).
- Derwisch and Lowe, (2015) conducted a study to demonstrate the use and benefits of system dynamics modeling in impact evaluation of the private sector development programmes.

The following are the benefits and characteristics of systems modelling (Freeman et al., 2014)

- Systems thinking views the system of concern in a systemic way. Systems thinkers put into consideration the ethical and moral issues around, as to how much to view the system as interconnected with the rest of the world, or parts of it, and what the effects of intervening in the system will be to any concerned stakeholders.
- System modelling enables analysis of potential interventions in existing systems to be done through scenario analysis.
- System modelling allows the modeler to consider perspectives not usually included in the more traditional analysis for policy making such as cost-benefit analysis
- System modelling doesn't model individuals, but empirical quantities that are associated with aggregates of individual behaviors.

2.3 Application of the system dynamics methodology in manufacturing

Table 1 illustrates the application of system dynamics approach in solving manufacturing problems.

Table 1: System dynamics approach to solve manufacturing problems

Author	Main topic	Findings
Ortega et al. (2017)	Development of a system dynamics model based on Six Sigma methodology	A dynamic model was proposed to analyse the complexity associated with the manufacturing systems and improve the performance of the process through the Six Sigma philosophy. The results showed an improvement in the process performance by increasing the level of sigma allowing the validation of the proposed approach.
Haddad and Otayek (2018)	Addressing the challenge of lean manufacturing sustainment with system dynamics modeling: a case study on apparel manufacturing in a developing country	The potential impacts on the manufacturing system were assessed using a system dynamics model since lean improvements are typically difficult to sustain over the long term, the system dynamics model was simulated over 6 months' period to ensure the achieved benefits were sustained. The results showed great process improvement.
Thirupathi et al. (2019)	Application of system dynamics modelling for a sustainable manufacturing system of an Indian automotive component manufacturing organisation: a case study	The objective of the study was to build an appropriate system dynamics model to identify areas required for sustainable improvement in an automotive component manufacturing organisation. Factors influencing sustainable initiatives were analysed by developing a model using a system dynamics approach. Suitable performance indicators were identified and used for carrying out the analysis.
Ho (2015)	Application of a system dynamics model to improve the performance of make-to-order production	A System Dynamic (SD) model of make-to-order production was constructed. The study revealed that SD provides a valuable decision support tool through the application of computer software. Furthermore, the organisation can duplicate the model that was created to predict its problems by changing its input functions and policies only.
Duvvuru et al., (2012)	A system dynamics model for studying manufacturing outsourcing cost dynamics	A system dynamics model was constructed, to understand how various factors evolve and work together over time to influence the cost-benefit balance in outsourcing. The developed model can be used by outsourcers to evaluate potential suppliers and formulate outsourcing policies that can ensure sustained profitability.
Dung Ho et al. (2018)	Using system dynamics approach to examine the impact of Enterprise Resource Planning and Lean on manufacturing performance	A system dynamics approach is used to illustrate how the performance changes under different scenarios using the real data of a case study at the textile and garment industry.

3. The system dynamics Methodology

Systems dynamics models are created from five stages: problem articulation, formulation of a dynamic hypothesis, formulation of a simulation model, testing of the model, and policy design and evaluation (Sterman, 2000).

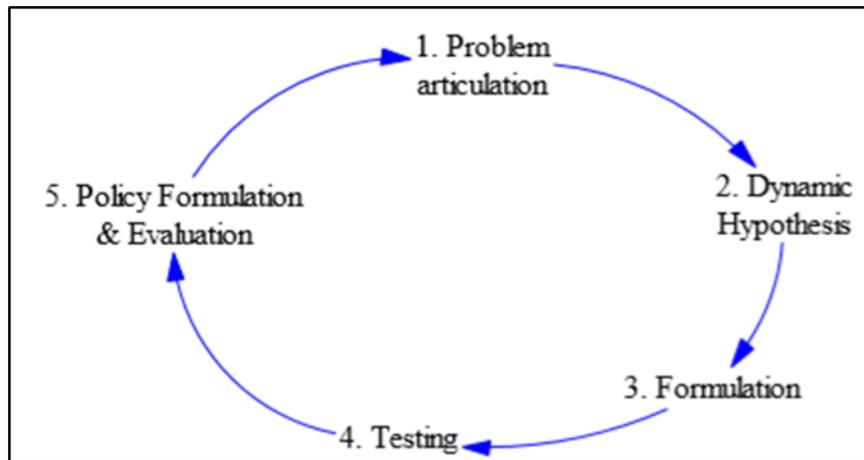


Figure 1. System dynamics modelling process

3.1 Problem articulation

Problem articulation is the most important step in modeling. It involves defining the problem, identifying key variables to be considered in the modeling process, and determining key variables (Sterman, 2000). A clear purpose goes a long way in clarifying the elements that should be included in the model.

Theme selection: What is the problem? Why is it a problem?

Key variables: What are the key variables and concepts we must consider?

Time horizon: How far in the future should we consider? How far back in the past lie the roots of the problem?

Dynamic problem definition (reference modes): What is the historical behavior of the key concepts and variables? What might their behavior be in the future?

Figure 2: Problem articulation (Sterman, 2000)

For defects reduction in the automotive manufacturing industry, problem articulation involves studying the background of the problem. Quality tools such as check sheets, cause and effect diagrams, Pareto charts, and flow charts can be used to gather this information.

Check sheets

It is a structured sheet prepared in software or manually record book. It may be called as a database of the location of defects, causes of defects, frequency of defects. It is highly recommended to save all data in the Check Sheet electronically because, from a database, any record can be found easily (Hasan, Islam and Dutta, 2020). The main advantages of check sheets are that it is very easily to apply and understand, and it can make a clear picture of the situation and condition of the organisation.

Cause and effect diagram

Cause and effect diagrams look like a skeleton of fish, it is a problem-solving tool that investigates and analyses systematically all the potential or real causes that result in a single effect. This tool also develops a common understanding of cross-functional team on the factors which causes a problem. The generic categories of the cause and effect diagram are usually five elements (causes) such as man, method, machine, material and environment.

Pareto Chart

Pareto chart is used to figure out the different kind of “nonconformity” from data figures, maintenance data, repair data, parts scrap rates or other sources. The Pareto analysis helps to identify different defects and classify them according to their significance.

Flow chart

A process flowchart is a smart representation of all process with standard symbols, material etc. In case of any failure in production or to solve a new type of defect rapidly, it becomes easy to find the root cause or source of the defect from the process flow chart.

3.2 Dynamic hypothesis

Formulation of dynamic hypothesis involves the generation of initial hypothesis and mapping, based on known theories of the problematic behavior (Sterman, 2000).

Initial hypothesis generation: What are current theories of the problematic behavior?

Endogenous focus: Formulate a dynamic hypothesis that explains the dynamics as endogenous **consequences of the feedback structure. Mapping:** Develop maps of causal structure based on initial hypotheses, key variables, reference modes, and other available data, using tools such as: Causal loop diagrams, Stock and flow maps,

Figure 3: Dynamic hypothesis

This step involves conducting a literature review, studying existing theories helps gain knowledge on the vital elements for inclusion in the model. Tools such as causal loop diagrams and stock and flow maps are used to develop maps of casual structure based on initial hypothesis and key variables. Simulation software’s i.e. Stella, Vensim and AnyLogic are used for mapping and simulation of causal loop and stock and flow diagrams.

Causal loop diagram

Causal loop diagrams are an important tool to represent a system’s feedback structure by capturing hypotheses about causes of dynamics and communicating important feedbacks believed to be responsible for the system’s behavior. A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram.

Stock and flow diagram

A stock and flow model helps in studying and analyzing the system in a quantitative way; such models are usually built and simulated using computer software. A stock is a term for any entity that accumulates or depletes over time. The flow is the rate of change in a stock.

Table 3.2 illustrates the Building Blocks of the Stock and Flow Diagrams.

Table 2: Building Blocks of the Stock and Flow Diagrams

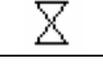
Stocks represent entities in the system where contents and levels can fluctuate during the period of simulation. Content of levels is cumulative of behaviour in previous time intervals.	
Flows represent movements of entities in the system. Equations governing flow provides the rate of the flows. Flows can be physical or abstract	
Valves control flows	
Sources and sinks are indicated with clouds. A source represents the stock from which a flow originate outside the boundary of the model arises. Sinks represent sinks into which flows leaving the model drain.	
Converters represent variables influencing behaviour of stocks and flows, e.g. the gravity constant will be defined by a converter.	
Connectors represent linkages between various elements in the system.	

Figure 2 illustrates an example of stock and flow diagram for defect creation and elimination of an equipment.

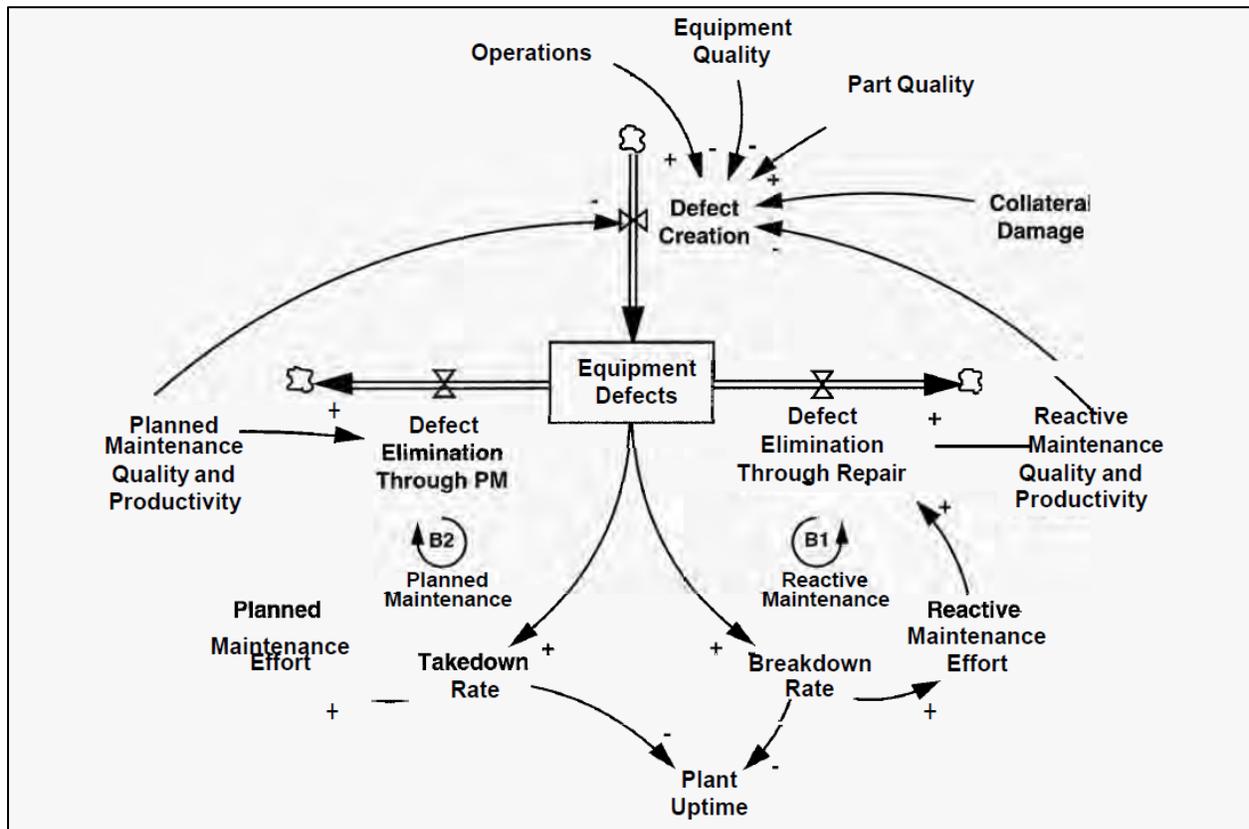


Figure 4: Defect creation and elimination (Sterman, 2000, 68)

3.3 Formulation

Formulation encompasses moving from the conceptual realm of the diagram to a fully specified formal model, complete with equations, parameters, and initial conditions. This stage of the modelling process helps recognize and resolve contradictions that went unnoticed during the conceptual phase (Grobbelaar, 2006).

In automotive manufacturing, this information can be obtained from data collected during the problem articulation stage, in some cases where data is not available, the modeler will have to make estimations based on knowledge, experience or consulting with experts in the area where research is conducted, for example, the quality control department.

<p>Specification of structure, decision rules. Estimation of parameters, behavioral relationships, and initial conditions. Tests for consistency with the purpose and boundary.</p>

Figure 5: Formulation

3.4 Testing

Testing involves far more than a replication of historical behavior, every variable must correspond to a meaningful concept in the real world. Models must be tested under extreme conditions, conditions that may never have been observed in the real world. Extreme conditions, along with other tests of model behavior, are critical tools to discover the flaws in your model and set the stage for improved understanding (Sterman, 2000). To pass these tests, the model must behave realistically no matter how extreme the inputs or policies imposed on it (Grobbelaar, 2006). The methods used to test the above includes both the direct inspection of the equations as well as simulation.

An example of such a test for the reduction of defects shown in figure 2, will be to study the behavior of the system if the number of initial defects, defect creation rate, and defect elimination through planned maintenance rate is increased or reduced. A realistic reaction to the above situation would be for the defects to drop.

<p>Comparison to reference modes: Does the model reproduce the problem behaviour adequately for your purpose? Robustness under extreme conditions: Does the model behave realistically when stressed by extreme conditions? Sensitivity: How does the model behave given the uncertainty in parameters, initial conditions, model boundary, and aggregation?</p>

Figure 6: Testing

3.5 Policy formulation and evaluation

Policy design includes the creation of new strategies, structures and decision rules. The robustness of policies and their sensitivity to uncertainties in model parameters and structure must be assessed, including their performance under a wide range of alternative scenarios. The interaction of different policies must also be considered. Design of policy and new strategies are created based on simulation and sensitivity analysis results. For defect elimination in manufacturing process, policy formulation and evaluation may involve implementation of resources for defect reduction, depending on the nature of the root cause. Resources for process improvement include implementation of planned and preventative maintenance, employees training and development, employee's incentive and motivation (Ezeanyim et.al, 2015). The impact of the resources on the system are tested using simulation models and sensitivity analysis runs.

<p>Scenario specification: What environmental conditions might arise? Policy design: What new decision rules, strategies, and structures might be tried in the real world? How can they be represented in the model? “What if. . .” analysis: What are the effects of the policies? Sensitivity analysis: How robust are the policy recommendations under different scenarios and given uncertainties? Interactions of policies: Do the policies interact? Are there synergies or compensatory responses?</p>

Figure 7: Policy formulation and evaluation

4. Causal Loop diagram for reduction of defects in automotive manufacturing

Figure 5 illustrates an example of a basic causal loop diagram (CLD) for reduction of six automotive manufacturing defects namely: Dent, high spot, sealer damage, paint damage, dirt and poor fit. The CLD was generated using Stella software version 9.1.4.

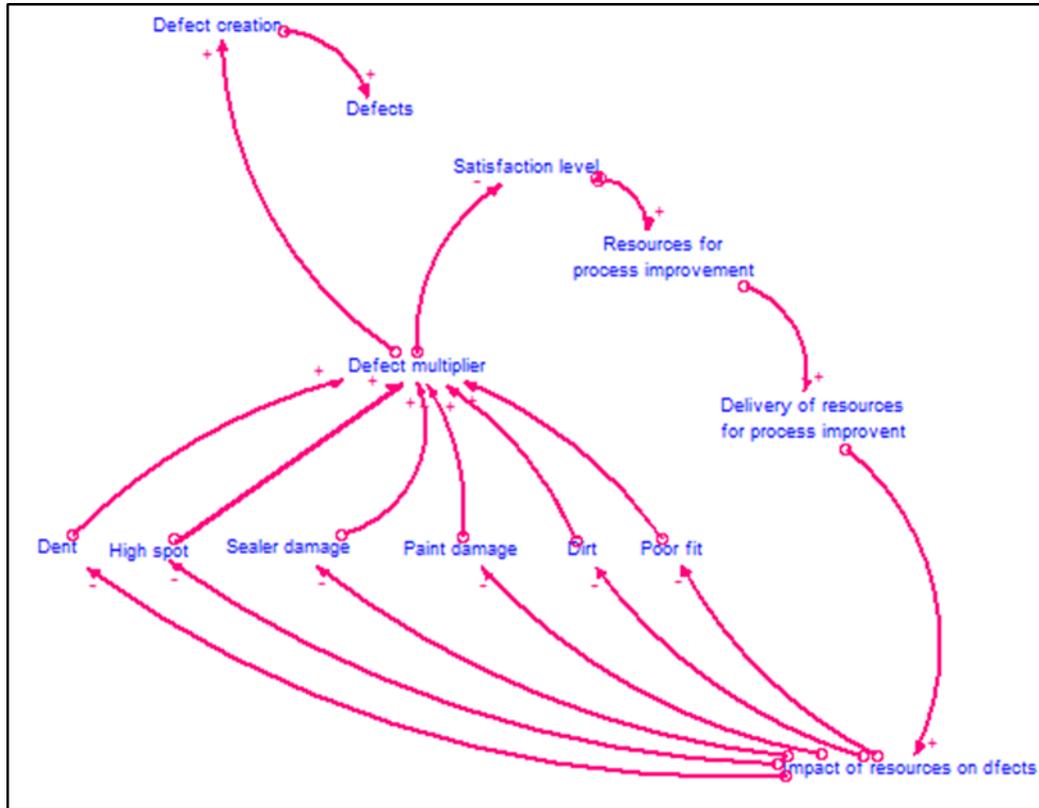


Figure 5: Causal Loop Diagram for defect reduction in automotive manufacturing

The CLD implies that the factors that contribute to the defect multiplier are dent, high spot, sealer damage, paint damage, dirt and poor fit. It is observed that as the defect multiplier increase, the satisfaction level will decrease. Satisfaction level determines how much resources are needed for process improvement. Low satisfaction level mean more resources for process improvement. The more resources for process improvement, the greater the impact on the factors contributing to defects thus, in turn will reduce defects.

5. Results

From the simulation results obtained below it can be observed that the defect creation rate declined from 160 to 83 over the period of 3 months after the implementation of resources for process improvement. Thus, the system dynamics methodology can be utilized in capturing and understanding the dynamic complexity of defect creation and reduction process in automotive manufacturing industry.

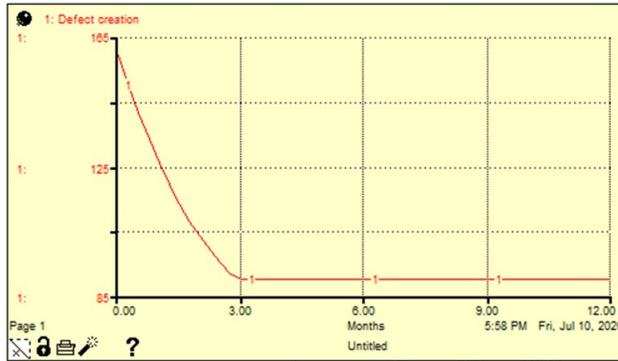


Figure 6: Defect creation simulation results

6. Conclusions and future work

This paper aimed at discussing the system dynamics methodology for reduction of defects in automotive manufacturing industry. The five steps of system dynamics modeling process were discussed into details and a causal loop diagram was developed using Stella software version 9.1.4. The study showed that system dynamics tools can be useful in capturing and understanding the dynamic complexity of defect creation and reduction in automotive manufacturing industry.

For similar future studies additional variables (i.e. other factors that affect the defect creation process in automotive manufacturing process) that may be linked to the problem of study must added and taken into consideration, this can help achieve more precise results.

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Biographies

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