

Titre: Contributions to Continuous Improvement Management Using its Variables to Measure Productivity, Employee Engagement and Participatory Management
Title:

Auteur: Rafael Alencar de Paula
Author:

Date: 2022

Type: Mémoire ou thèse / Dissertation or Thesis

Référence: Alencar de Paula, R. (2022). Contributions to Continuous Improvement Management Using its Variables to Measure Productivity, Employee Engagement and Participatory Management [Thèse de doctorat, Polytechnique Montréal].
Citation: PolyPublie. <https://publications.polymtl.ca/10788/>

 **Document en libre accès dans PolyPublie**
Open Access document in PolyPublie

URL de PolyPublie: <https://publications.polymtl.ca/10788/>
PolyPublie URL:

Directeurs de recherche: Samuel Bassetto, & Yuvin Adnarain Chinniah
Advisors:

Programme: Doctorat en génie industriel
Program:

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Contributions to Continuous Improvement Management

Using its Variables to Measure Productivity, Employee Engagement and Participatory Management

RAFAEL ALENCAR DE PAULA

Département de mathématiques et de génie industriel

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

Génie industriel

Août 2022

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cette thèse intitulée :

Contributions to Continuous Improvement Management

Using its Variables to Measure Productivity, Employee Engagement and Participatory Management

présentée par **Rafael ALENCAR DE PAULA**

en vue de l'obtention du diplôme de : *Philosophiæ Doctor*

a été dûment acceptée par le jury d'examen constitué de :

Soumaya YACOUT, présidente

Samuel-Jean BASSETTO, membre et directeur de recherche

Yuvin Adnarain CHINNIAH, membre et codirecteur de recherche

Fabiano ARMELLINI, membre

Mickaël GARDONI, membre externe

DEDICATION

*À ma famille,
pour l'amour inconditionnel.*

*« Education is
the ability to perceive the
hidden connections between
phenomena. » - Václav Havel*

ACKNOWLEDGEMENTS

I am primarily and most grateful to my supervisor Dr. Samuel-Jean Bassetto, for his guidance, inspiration and enthusiastic creativity. The support and counsels of my co-director Dr. Yuvin Adnarain Chinniah. And the support and directions of the committee Dr. Soumaya Yacut, Dr. Mickaël Gardoni and Dr. Fabiano Armellini. The work would not be possible without the companies' partners, Wajax Industrial Solutions and other companies who open their doors and shared their challenges. The support of Mittacs, represented by Wissem Maazoun. Also, the FRQS (Fonds de recherche du Québec - Santé) for the support in research program with hospitals. It is also important to thank two friends (and many others) who spend uncountable hours reviewing and listening myself talk about this topic, Dr Luis Antonio Pereira de Lima and Dr. Abdallah Ben Mosbah. This thesis is lovely dedicated to my parents and family, mother Maria Nadir Alencar da Silva de Paula, father Mauricio de Paula and sister Camila Alencar de Paula. Their support, encouragement, patience, and example have guided me throughout my life. The distance, cold days and so important family events missed due this project along the years seemed shorter because of your love, a warm and deep thanks to you, my family! Without Monique Alves Matheus, this personal project would never have been started. Her planning skills, hard work and motivation made me believe it was possible. My wife and son provided the closest support and love during this challenging time. Thanks, Berengere Orjubin, for all the support and patience during this period. And thanks, Valentin Orjubin de Paula; I hope this work can inspire you. Not necessarily on the engineering path but on the rewards of the long-term commitment to your education. If I say only two things to you: Never stop learning and serve others.

RÉSUMÉ

Objectifs - Explorer la relation entre un projet d'amélioration continue et les d'autres domaines qui ne sont généralement pas liés à l'amélioration continue, initialement la productivité, l'engagement des employés et la gestion participative. Proposer trois modèles mathématiques, le premier pour estimer la capacité de solution de problèmes, la productivité d'une équipe. Le deuxième pour estimer l'engagement des employés, et le troisième pour explorer la relation entre la gestion participative et l'amélioration continue. **Conception / méthodologie / approche** - Pour concevoir les modèles mathématiques, l'auteur a adapté le modèle prédateur et proie (également appelé de Lotka-Volterra). Les modèles ont été testés de façon théorique et aussi avec des données réelles. La première question est *"Quelle est la relation entre la physique sociale et l'amélioration continue?"* et la deuxième question: *"Comment ces modèles peuvent identifier d'autres variables présentes dans l'organisation du travail, comme par exemple, la productivité, l'engagement des employés et la gestion participative?"* Une revue de la littérature des 50 dernières années de recherche qui présente les principaux points concernant l'amélioration continue, la productivité, l'engagement et la gestion participative a été réalisée. Les modèles ont été conçus dans différentes versions et logiciels, mais principalement sous Netlogo et Matlab. Pour avoir de vraies données, un projet d'amélioration continue a été mis en œuvre dans une industrie. Avec les données de ce projet, le premier modèle a été testé. **Résultats** - La recherche suggère le lien entre la physique sociale et l'amélioration continue. Avec ce lien, cette recherche propose trois modèles grâce auxquels l'utilisateur est capable de mieux comprendre la productivité (et d'estimer le temps nécessaire pour un projet d'amélioration continue), de simuler l'état de l'engagement des employés, et aussi d'explorer l'impact de la gestion participative, **Originalité / Limitations** - Proposer des nouveaux modèles pour mesurer un comportement social comme gestion participative ou engagement exige des tests dans différents scénarios et domaines. Le travail présente une proposition et une première validation dans une industrie manufacturière. La poursuite du développement du travail dans d'autres industries et services, ainsi que la proposition d'autres variables et équations sont une continuation naturelle de ce travail.

ABSTRACT

Objectives - Explore the relationship between a continuous improvement project and other areas not usually related to the continuous improvement, initially productivity, employee engagement, and participatory management. Propose three mathematical models, the first to estimate a team's problem-solving capacity and productivity. The second is to estimate employee engagement, and the third is to explore the relationship between participatory management and continuous improvement. **Design/ methodology/ approach** - The author adapted the predator and prey model (also called from Lotka-Volterra) to design the mathematical models. The models have been tested theoretically and also with actual data. The first question is "*What is the relationship between social physics and continuous improvement?*" and the second question: "*How can these models identify other variables present in the organization of work, how for example, productivity, employee commitment, and participatory management?*" A review of the literature of the last 50 years of research presents the main points concerning continuous improvement, productivity, commitment, and participatory management have been carried out. The models have been designed in different software, but mainly under Netlogo and Matlab. A continuous improvement project has been implemented in the industry to test the model with actual data. The author tested the first model of this work with the data from this project. **Results:** The research suggests the link between social physics and continuous improvement. With this link, this research proposes three models by which the user can better understand productivity (and estimate the time needed for a continuous improvement project), simulate employee engagement, and explore the impact of participative management. **Originality / Limitations** - Proposing new models to measure social behavior, like participatory management or employee engagement, requires testing in different scenarios and domains. The work presents a proposal and the first validation in the manufacturing industry. The further development of work in other industries and services and the proposal of other variables and equations are a natural continuation of this work.

TABLE OF CONTENTS

DEDICATION	iii
ACKNOWLEDGEMENTS	iv
RÉSUMÉ.....	v
ABSTRACT	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	x
LIST OF FIGURES.....	xi
LIST OF EQUATIONS	xiii
LIST OF SYMBOLS AND ABBREVIATIONS.....	xiv
LIST OF APPENDICES	xv
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 LITERATURE REVIEW	11
2.1 Continuous Improvement and Productivity	11
2.2 The Employee Engagement and Continuous Improvement Relation	15
2.3 How Continuous Improvement is Related to Participatory Management.....	21
2.3.1 Collective Intelligence.....	22
2.3.2 Communities of Practice	23
2.3.3 Idea Flow	23
2.3.4 Social Pressure	24
2.4 Lotka-Volterra Model	24
2.5 Multi-Agent Systems Simulation	28
2.6 Alternatives for the Proposed Models	30
2.7 Conclusion.....	33
CHAPTER 3 METHODOLOGY	34

3.1 Research Objectives	34
3.2 Central Methodology.....	35
3.3 First tool - Lotka-Volterra Model Adaptation.....	36
3.3.1 Simulation Model and Database	39
3.3.2 How Model was Tested.....	42
3.4 Second tool – Using CI Variables to Measure Employee Engagement.....	44
3.4.1 The Engagement Model	45
3.4.2 Proposed Methodology to Test the Model	52
3.4.3 Expected Results from this Model and First Discussion.....	53
3.5 Third tool: Simulating the Impact of Participatory Management	54
3.5.1 Model Features	56
3.6 Conclusion.....	61
CHAPTER 4 RESULTS	62
4.1 First Tool - Lotka-Volterra Model Adaptation for Productivity Model.....	62
4.1.1 Analyze Before the Project	63
4.1.2 Analyze During the Project	66
4.1.3 Conclusion.....	72
4.2 Third tool-Simulation Continuous Improvement Effect in Participatory Management ...	73
4.2.1 Results	73
4.2.2 Conclusion.....	81
CHAPTER 5 GENERAL DISCUSSION	83
5.1 Main Results and Contributions	83
5.2 Questions for Discussion.....	85
CHAPTER 6 CONCLUSION AND RECOMMENDATIONS.....	89
6.1 Conclusion.....	89
6.2 Limitations	89
6.3 Recommendations and Future Work.....	90
REFERENCES.....	92

APPENDICES.....	99
-----------------	----

LIST OF TABLES

Table 2.1 Productivity Main Features	14
Table 2.2 Employee Engagement and CI variables	20
Table 2.3 Employee Engagement Level	21
Table 2.4 Alternative's pros and cons (Source: The author).....	32
Table 3.1 Relation between the variables.....	38
Table 3.2 Database for the mathematical model	40
Table 3.3 Values of the variables	44
Table 3.4 Comparison Between the Models	45
Table 3.5 Employee Engagement and CI variables	51
Table 4.1 Model settings	75

LIST OF FIGURES

Figure 1.1 Productivity level (Source: U.S. Bureau of Labor Statistics)	2
Figure 1.2 Relation between the subjects (Source: The author)	8
Figure 2.1 Basic concept of productivity (Source: Sink, 1985)	13
Figure 2.2 Collective intelligence (Source: Surowieck, 2004)	22
Figure 2.3 LV Equilibrium (Source: Pilovsky et al. 2001)	26
Figure 2.4 Causal loop diagram Lotka-Volterra model (Source: The author)	27
Figure 2.5 Multi-agent system characteristics (Source: Schäfer, L & Albrecht, S, 2019).....	29
Figure 2.6 Determination of price and quantity (Source: Principles of Economics – University of Minnesota).....	31
Figure 3.1 Central methodology for the work (Source: The author)	35
Figure 3.2 Causal loop of the first tool (Source: The author)	38
Figure 3.3 Bloc diagram of the mathematical model (Source: The author).....	42
Figure 3.4 Checklist for the Success fee (Source: The author)	47
Figure 3.5 Checklist for Communication (Source: The author).....	48
Figure 3.6 Checklist for the Team Energy (Source: The author).....	49
Figure 3.7 The model causal loop (Source: The author).....	50
Figure 3.8 Netlogo Interface – Commands details.....	57
Figure 3.9 Worker Vision.....	58
Figure 3.10 Visual Indicator between the two scenarios	60
Figure 3.11 Populations Balance and Problems solved Indicators	61
Figure 4.1 Workers and Problems Total - Before the Project	63
Figure 4.2 Correlation between Prob Real and Wk Sim - Before the Project.....	64

Figure 4.3 Simulation of Workers and Problems - Before the Project	65
Figure 4.4 Workers and Problems Total - During the Project	66
Figure 4.5 Workers Real and Simulation	67
Figure 4.6 Problems Real and Simulation.....	69
Figure 4.7 Relation Real and Simulation	70
Figure 4.8 Simulation at the End of the Project	71
Figure 4.9 Test #1 Participatory management model	77
Figure 4.10 Test #2 PM model.....	77
Figure 4.11 Test #3 PM model.....	78
Figure 4.12 Test #5 Pm Model.....	79
Figure 4.13 Test #9 Pm Model.....	80
Figure 4.14 Test #10 Pm Model.....	81
Figure C.1 Test #4 Pm Model	113
Figure C.2 Test #6 Pm Model	113
Figure C.3 Test #7 Pm Model	114
Figure C.4 Test #8 Pm Model	114

LIST OF EQUATIONS

Equation 1 Lotka-Volterra Main Equation (Volterra, 1926 and Murray, 2002).....	25
Equation 2 Derivative of problems along the time (Source: The author)	36
Equation 3 Derivative of workers along the time (Source: The author)	36
Equation 4 Derivative of engagement along the time (Source: The author).....	45

LIST OF SYMBOLS AND ABBREVIATIONS

CIA - Continuous Improvement Actions

CIP - Continuous Improvement Project

CIM – Continuous Improvement Methodology

DR – Death Rate

EE - Employee Engagement

GPD - Gross Domestic Product

GR – Growth Rate

LC - Learning Curve

MAS - Multi-Agent System

MASS - Multi-Agent System Simulation

ODE - Ordinary Differential Equation

PM - Participatory Management

KPI - Key Performance Indicators

LIST OF APPENDICES

Appendix A MATLAB CODE FOR THE FIRST MODEL.....	99
Appendix B NETLOGO CODE FOR THE THIRD MODEL.....	103
Appendix C TESTS RESULTS FOR THIRD MODEL	113

CHAPTER 1 INTRODUCTION

Continuous improvement and social physics relation

Historically, the continuous improvement project (CIP) leader and the company's managers will look with attention to the results of three areas: Muda (reduction of waste), Mura (reduction of errors), and Muri (reduction of work overload) (Landry & Beaulieu, 2021). Although these reductions are fundamental for any company, the author of this work proposes a new view on the possible results of a CIP. With the question, "*How many errors did the project cut?*" The manager will be able to ask, "*What is my team's capacity to solve problems?*" or "*What is my team's engagement level?*". Following this line, this work proposes establishing a new relationship between a continuous improvement project and social physics (or social dynamics).

According to Ball (2004) and Pentland (2015), social physics is the study of a group of people's behavior using mathematics or physics theorems. The term is appropriate for this research due to the methodology applied: Study a group performing a continuous improvement project and use a mathematical model to analyze three areas. The author uses the term "Social physics" to englobe three areas in this work. First: Economics. The productivity or capacity of a team to solve problems. Second: Psychology, employee engagement, or team engagement to work together to solve problems. And finally, management. The impact of a Continuous Improvement Project (CIP) in participatory management.

The initial question and the basis of this research are: "How the *continuous improvement methodology* can impact *productivity, employee engagement, and participatory management?*". To answer this question, the author identifies the main variables of the sciences cited and proposes a series of Ordinaries Differential Equations (ODE) to measure these variables. The methodology proposed in this work is to implement a COP to get actual data and analyze the derivative of these variables over time.

The empirical hypothesis of this work is to test a new way to measure the variables of the sciences cited: "*A CIP can propose a more accurate or new method to measure productivity, employee engagement, and participatory management.*" The hypothesis questions the actual methodology used to measure the variables indicated. The actual method to measure productivity is to divide the

total of inputs in a process by the total of outputs; the hypothesis proposes that a CIP can provide an indicator to better measure productivity, in this case, the capacity of a team to solve problems. With this method, the manager can better define a strategy to reduce the real problems in her company.

Similarly, the work proposes a new measure of employee engagement (EE). This method proposes an alternative to the classic survey method applied by several companies and universities. This method analyses the data from a CIP and compares the variables present in the EE classic survey method. The third and last model proposed tests the capacity of the equations to evaluate participatory management. The problems related to each topic are explained below.

The constant pressure to increase productivity

Statistics Canada¹, the U.S. Bureau of Labor statistics², and many other countries are decreasing labor productivity. It is not hard to feel the pressure always to increase productivity. According Moore (2012) and Georganas (2015), the pressure to increase productivity is negative to the product itself. The graphic below shows the productivity levels in the USA.

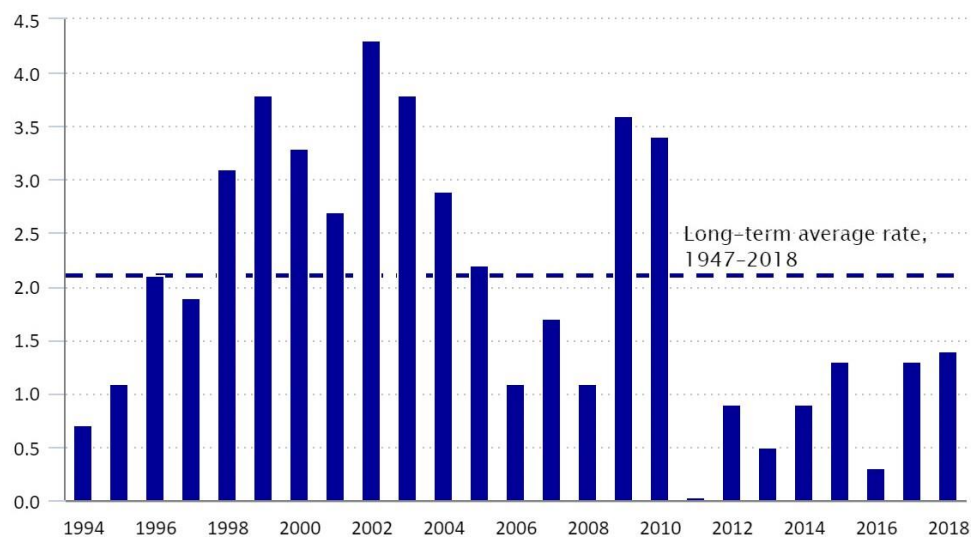


Figure 1.1 Productivity level (Source: U.S. Bureau of Labor Statistics)

¹ <https://www150.statcan.gc.ca/n1/daily-quotidien/210604/dq210604b-eng.htm>

² <https://www.bls.gov/news.release/prod2.nr0.htm>

One problem the author Moore and Georganas identified is the methodology used to measure productivity. The following paragraphs define productivity better, and later in chapter 3 – Methodology, the author of this work explores the model to measure productivity according to the capacity of a team to solve problems.

According to Tangen's article from 2005, companies have a specific brain or department to think about "how to improve productivity?" How can my company produce more with fewer resources (time, manpower, prime resources, money)? These "departments" were formally designed since the industrial revolution, and since the beginning of any production service, they have been important (Tangen, 2005).

The problem with these departments is the methodology to measure productivity. The basic idea of producing more with less seems optimistic. In the end, the workers produce more in less time, and naturally, they will have more free time. Nevertheless, it is clear that this is not the final result; with more free time, the companies want to produce even more.

Several initiatives are made to push forward productivity, and technology has helped companies to communicate faster and produce as much data as was ever imagined. Although this increment in communication and technology, the productivity has not increased as expected by the shareholders. The managers are stressed as never before, and work-related health problems have also increased as never before (Lesener et al., 2020). The U.S. Bureau of Labor Statistics³ shows the decay in productivity between 2005 and 2018 when compared with the historical average from 1948. How the managers and others productivity responsible can overcome this trend of low productivity although high investments in faster production and communication?

The continuous improvement project is one of the "tools" or methodologies available to help managers in this challenge. The first model presented in this work explores this area and discusses one important asset of a CI project: "Human resources". As a manager, how much manpower should I allocate to my continuous improvement project? The tool presented here simulates a scenario where it is possible to define the resources needed according to the number of problems in the company and not the human resources available as usual in the market.

³ <https://www.bls.gov/k12/productivity-101/>

Together with the productivity problem, this work explores the Employee Engagement side of low productivity and its limitations. Although the work does not imply a direct relationship between engagement and productivity, some studies discuss the increase in productivity when observing an augmentation in engagement (Kahn, 1990; Gallup, 2017; Gallup, 2021).

Lack of engagement and methodology to measure the engagement

The first step for a company to select the right person is to define the job description. The right skills, abilities, language(s) spoken in the company, and general knowledge. Partners with the right skills and abilities could do the job right the first time. But this is just the first step to doing the job with quality. Charles Woodruffe, in his article “The crucial importance of employee engagement” (Woodruffe, 2006) defends the simple idea that after hiring the employee, the company has an employee-life-long time to keep the employee motivated. As he said: The high direction of the company cannot believe in the idea of a fully motivated employee just because he is hired and now is receiving a salary. His short article lists thirteen points related to Employee Engagement (EE) and ten practical points to engage them.

According to the 2017 Gallup Q12 report⁴, 70% of the employees are not actively engaged in the U.S.A. The 70% not actively engaged can cause a loss of \$450 billion to \$550 billion per year just in the USA. In 2021, the new Gallup report showed a worldwide evaluation defending the loss of 8.1 US trillion dollars in GDP globally due to the lack of engagement⁵.

Still, according to the Gallup report, this financial loss is caused when productivity variables are compared between the engaged employee and the other two groups measured in their survey: “not engaged and actively disengaged employee”. Compared with the actively engaged groups, the other two groups report more work missed (3.5 more days per person per year) and more days of work missed for illness (0.55 days per person). This cost does not consider indirect costs, such as turnover, safety, or healthcare costs. However, just the direct costs are expressive enough. Based

⁴ <https://www.gallup.com/workplace/238085/state-american-workplace-report-2017.aspx>

⁵ Gallup State of the global workplace 2021 – <https://www.gallup.com/file/workplace/349484/state-of-the-global-workplace-2021-download.pdf>

on this high economic impact and considering the lack of studies related to this problem, this work proposes a study of the main social variable related to engagement.

Another problem with EE is the way it is measured. Although surveys are an excellent start, they will be rapidly archaic. The employees will probably answer based on their previous experiences in the company. Maybe considering only the last few days or weeks. Also, the answers could present a personal bias. Mind-sets based on beliefs or answers based on “What would my boss like to see?”. However, the profound Gallup tradition, their (and from other similar companies) methodology to measure the global engagement level is based primarily on statements affirmed by the employees.

The authors Little & Little (2006) defend that the classical EE method has a problem constructing the word engagement. To better understand the importance of the suitable construction of the word “Engagement,” this work uses a comparison with a person’s maturity level. To prove a maturity level, just words or statements are not sufficient. Actions and experiences are a requirement. The authors Little & Little (2006) also defend this point in their paper “Employee Engagement: Conceptual Issues.”

The psychological nature of the word “construction” cannot be founded just by statements. Any person must manifest engagement and not just refer to it through surveys. The previous results and experiences will prove if the candidate could be an engaged person in that specific past moments. In this way, based on the premise that the employee needs some specific factors (Attridge, 2009; Bakker & Leiter, 2015; Fuller, 2014) to engage in a job, it is only possible to measure an ephemeral engagement level or an engagement into a determined activity.

Following the same research line of this work, professor Briner (2009) also explores the problem and defends the point of the lack of research to compare the results of the company’s “engagement” with other financial and quality results. For example, compare results with efficiency and prove the hypothesis that more engaged employees will produce more. Similar studies are done by engagement companies such as Gallup or BlessingWhite, but not peer-reviewed publications. The closest analyses related to this topic are the Gallup “The meta-analysis” which compared different results of the company with the Q12 (the questionnaire to measure EE from Gallup). The book “First, break all rules” (Buckingham & Coffman, 2014) by Gallup employees details this relation and more about the meta-analysis.

Both authors, professor Briner, and B. Little et al. endorse the importance of an engagement survey's previous and after actions. A fundamental tool for a PREVIOUS employee engagement definition and measure is the relation with other similar measurements such as "job satisfaction". For the moment, after the engagement survey, the BlessingWhite company defends in their report of 2011 (BlessingWhite Research, 2011) that asking about engagement but not following the results with the necessary actions could reduce the engagement level of the employees. It is necessary to present to the employees a structured action plan based on the survey results. The action plan will motivate the employees to keep improving their daily activities due to trust in the company's management. On the other hand, measuring engagement but not providing proper feedback can create the common saying: "Nothing will change in the company."

The author defends the hypothesis that a continuous improvement project could provide all the tools needed by the employees to be engaged, so once a CI methodology is implemented, the model explored by this author could measure and predict the engagement level in the company. The work also defends the limits of employee engagement, indicates the general group engagement, and compares it with productivity and the previous discussion. The work will not discuss this individual EE level and the neurological side of engagement.

Relation between CIP and Participatory management – How to decide the company's management style needs.

Participatory management is fundamental to any continuous improvement project. It is the method applied to companies to empower their employees with management skills. Making decisions, providing ideas, and establishing goals are some of the management skills needed in participatory management and necessary in a continuous improvement project. Even if its importance is evident, the methods to implement this management style are not straightforward or easy (Bernardes, Andrea et al., 2012 and 2015). The authors defend that there are several management books in the market, and it covers the different management methodologies, but it does not define which type is appropriate for the company in question. The third and last part of this work explains the bases of participatory management and explores the connections between participatory management and continuous improvement. The idea of the model and the use of the multi-agent systems simulation is the compare two scenarios: One where the employees can interact and work together and the

second where the employees work individually. The tool briefly discusses the importance of adapting the management style to the company's learning curve.

The model discussion explores the bases of a simulation to compare participatory management with regular management. Furthermore, the results can help managers to adapt their management style to the actual level of the company.

With the question, hypothesis and problems addressed, the objective of this work is: *“To discuss and possibly establish a relation between a continuous improvement project and initially the three areas: productivity, employee engagement and participatory management.”*

This work uses different tools and areas of science to reach this objective, but the primary methodology is applying the scientific method. The author identifies the problems and proposes alternatives, in this case, new models for measuring the variables and testing the model to compare with the classic method.

For example, the classic method to measure employee engagement is to share surveys and imply the result from the employee's answers. To validate a new methodology to measure EE, the proposes: (1) Propose a mathematical model to measure the EE. (2) Measure the EE with the classic method, (3) implement a CIP in the company, (4) use the data from the CIP in the mathematical model proposed, (5) measure the EE with the classic method at the end of the CIP and (6) compare the results of the classic method with the proposed method.

To better understand the continuous improvement impact on these areas, the work is inspired by a classic tool for industrial engineering and management. This tool is the mathematical model called Lotka-Volterra, also known as the predator and prey model (Murray, 2002). This mathematical model is adapted in this work to compare the continuous improvement methodology with the predator-prey environment. This inspiration is one of the work's innovations and is not found similar in the literature review. Even with this lack of literature, the author was firstly inspired by the work of Zangwill and Kantor (1998, 2000).

In their work, Zangwill and Kantor proposed a new theory about the relationship between CIP, Lotka-Volterra model, and Learning Curve (LC). The idea is to compare the “balance behavior” of the Lotka-Volterra populations, predators and prey, with the CIP methodology. In this case, the improvement actions are the predators, and the manufacturing problems are the prey. This balance

behavior is the main feature of the Lotka-Volterra model, which is better explained in chapter 2, literature review.

Chapter 2 also details another model considered in this research, the supply and demand model. This model also works in equilibrium (Setterfield, 2003); the quantity of goods supplied by the producers equals the quantity demanded by the consumers. This equilibrium could be compared with the balance between the Continuous improvement actions and the manufacturing problems, as proposed in this work. But to continue Zangwill and Kantor's work, and mainly to the better fit of the Lotka-Volterra model, the author decided to use the LV as inspiration for this work.

The last model presented in this work explores another possible capacity of a CIP. The capacity to guide the managers in which management style the company will better respond. To do this, the author presents a multi-agent system (MAS) simulation tool. The MAS simulation was chosen because of its capacity to work with several agents simultaneously. The MAS can separate environments, define agents, and establish goals and actions for each agent. These features are not presented in the two first mathematical models.

The figure below displays the relationship between the three main areas discussed in this research.

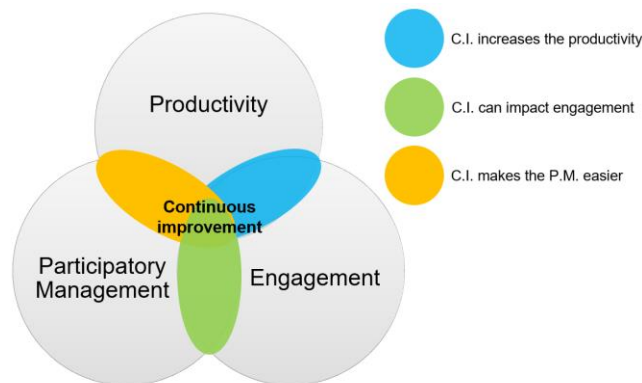


Figure 1.2 Relation between the subjects (Source: The author)

The figure suggests three hypotheses defended during this work. (1) The CIP can provide the necessary data measure and increase productivity. This data is provided when the employees dedicate part of their work hours discussing and sharing ideas, and the level of problems is continuously measured. The second hypothesis (2) claims that an employee participating in the continuous improvement project will (between other points) feel recognition, receive feedback,

and see the big picture of the process. This data will also be used to measure the EE. In addition, the employee will be more actively engaged in increasing productivity. Furthermore, more engaged employees have a high capacity to support participatory management. The cycle of CIP starts with a productivity analysis, goes to the engagement, and finishes with the management.

As cited previously, this work suggests a Lotka-Volterra model adaptation. The adaptation provides the following scenarios: (1) The continuous improvement actions (CIA) are the predator, and the manufacturing problems are the prey. The CIA and the manufacturing problems are measured in hours by the company. (2) The CIA and the manufacturing problems should co-exist and balance, with a limited number of problems established by the company. (3) The engagement will provide the necessary energy to search for the problems. Moreover, (4) participatory management can solve more problems than authoritative management. Chapter 2 – Literature review and chapter 3 – Methodology will deeper the definitions and details of each model.

Results of this work

The link between continuous improvement, productivity, employee engagement, and participatory management is an innovation not yet found in the literature. Additionally, the models introduced and the methodologies proposed are authentic and robust tools for managers to change their way of work. The work proposed three models. The first model, which measures the company's capacity to solve problems, called productivity, was tested the in a company in Montreal, Quebec.

As results, the test of the first tool revealed the difficulties of a theoretical model in a manufacturing environment. These difficulties are exposed and discussed in the chapter 4 – Results. Also, as a result, the model had positive feedback from the company's management. As a coherent and simple tool to estimate how much time the company should dedicate to continuous improvement. As an improvement point, the chaotic nature of the model can make the simulator feeble. A small change (up to the fourth number after the decimal) can change result and consequently change the hours suggested for the employee.

The second model presents an innovative methodology to measure employee engagement. This is a logical sequence for the first model, with the same database and a third equation. For this model, the necessary data and methodology to apply the model are explained. Furthermore, the third result is the introduction of the simulation of participatory management. This model adjusts the methodology using a multi-agent system simulation (MASS), which can avoid the chaotic behavior

of a system of equations. The model provides a clear view of the employee's role, simulated by the agents. As an improvement point, the model should better represent the balance between populations and implement more characteristics for the scenarios and agents. Chapter 3 - Methodology and the conclusion detail deeply the results and recommendations.

Publications and future publications

Although this is a classic thesis, the author published two articles based on the methods and results of this work. The articles are:

R. de Paula, E. Dimas, C.Laroche, S. Bassetto, "Measuring the dynamic engagement with a system of equations - Theory demonstration and initial analysis," *IEEE Systems Engineering Conference*, Orlando, Fl 2019 DOI: [10.1109/SYSCON.2019.8836889](https://doi.org/10.1109/SYSCON.2019.8836889).

Rafael Alencar de Paula, Abdallah Ben Mosbah, Yuvin Chinniah & Samuel Bassetto, "Towards a New Continuous Improvement Organization Based on Simulation", *Engineering Management Journal*, 2021 DOI: [10.1080/10429247.2021.1958630](https://doi.org/10.1080/10429247.2021.1958630)

Also, as detailed in the chapter 6, section 6.3, the author works on two other publications as a continuation of this work.

R. de Paula, A. Ben Mosbah, Y. Chinniah, S. Bassetto, "Toward a New Engagement Team Model - Proposition of the Methodology," - To be Submitted

R. de Paula, S. Bassetto, "Using CI data to decide which of the three managements strategy to use" - To be Submitted

Thesis organization

Chapter 1 is the introduction of this work, with the main problems, hypothesis, methods implemented and results. Chapter 2 is the literature review, or the review of the actual state of art. It includes the similar models, the main authors researching the topic, and the bases to each idea cited in this work. Chapter 3 is the methodology, explaining the operation or behavior of each idea proposed. Also, how to reply and test the ideas proposed in other scenarios and situations. This chapter is divided into three parts, each dedicated to one area researched: Productivity, employee engagement, and participatory management. Chapter 4 Results, explains the links and common points between the proposed results, tools, and methodology. Finally, the discussion in chapter 5 and the conclusion and future work are in chapter 6.

CHAPTER 2 LITERATURE REVIEW

The literature review presented in this work covers the complementary points to understand the tools and methodologies presented in further chapters. As introduced previously, each tool presented has a direct interaction with continuous improvement. The tools were not chosen without reason but instead because of their intersecting connection with continuous improvement.

The chapter explains the four parts: Continuous improvement and its relations with productivity, employee engagement, and participatory management.

2.1 Continuous improvement and productivity

Continuous improvement started to overcome the challenge of every company to remain competitive. Competitive means producing with high-quality and low cost. But it is not enough anymore. Companies must retain sufficient flexibility and meet rapidly changing customer necessities (A. Tharumarajah et al., 1996) (S. M. Jeon and G. Kim, 2016). This necessity seems actual, but the pressure to “produce more with less” resources dates for more than 70 years. Its origins were before 1950. It first happened through Tiichi Ohno and Shigeo Shingo’s concept “Just-in-time” production system. Just-in-time production, beyond other characteristics, was one of the first to apply a disciplined and organized methodology to the factories. Along with this methodology, a second characteristic is the quality movement and statistical reasoning applied by W. Edwards Deming. It is the beginning of the data collection (today, data analysis or data mining) and the Plan-Do-Check-Act (PDCA) cycle.

The description of continuous improvement changed a lot over the years. One of these changes was the advent of the term Lean Manufacturing, worldwide known after the book “The Machine that Changed the World” by Womack et al. (1991):

“Compared to mass production, it uses less of everything, half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Also, it requires keeping far less than half the needed inventory on site, resulting in fewer defects, and producing a greater and ever-growing variety of products.” (p.13)

After 24 years (in 2012), Alves et al. described lean with the following words:

“Lean production is evidenced as a model where the persons assume a role of thinkers and their involvement promotes the continuous improvement and gives companies the agility they need to face the market demands and environmental changes of today and tomorrow.”(p.16)

Instead of the old focus on reduction from 1988, Alves et al. focused their description on the model, thinkers, involvement, and market demands. A model is necessary to build a process and to design the agents who are participating in this process. It is easier to understand the environment and determine different scenarios through models.

This view focused on models is applied in this work entirely. The first model presented in this work helps managers estimate their teams’ actual capacity, or as the author called it, the productivity model. The following paragraphs details the history of productivity and related models.

Productivity is a branch of economics, and the measurement of production efficiency primarily defines it. The term was first used in 1766 by François Quesnay. This first moment was mainly to improve the production efficiency of agricultural production. The term has been wildly used since then, and sometimes the definition differs from the original Quesnay first proposition. According to (Sumanth, 1994), productivity is generally defined as the relation of output (i.e., produced goods) to input (i.e., consumed resources) in the manufacturing transformation process. There are two areas to reinforce and define de productivity: First, the verbal definition, *“what aims to define the concept of productivity as spoken in the company,”* and second, the daily definition: *“To perform a task with excellence and fast.”*

On the other hand, the mathematical definition is a measure of performance. A measure of the production to improve it. In a match with the purpose of this work, productivity is defined and leaned closer to the verbal definition.

Productivity is a universal term normally found in different topics and discussions. The origin of the word productivity is not understood, but according to the Oxford English Dictionary, it comes directly from the medieval Latin *“productivus.”* And it is a reference to the *“quality of being productive.”* The French Journal of Agriculture, Trade, and Finance used the term by the writer François Quesnay (1766). Quesnay referred to the *“productive class”* or the workers. The people who produce goods for the owners or the *“sterile class.”*

It is not far apart from the first Industrial Revolution in Europe. This revolution was led by Great Britain in the period starting in 1760. Although the quiet start by some innovative industries, the

revolution was considered complete, which means the majority of the sectors were industrialized around 1840 (Horn et al., 2010). Now the work was centralized in the same factory or local. More prominent manufacturers and industries replaced small local businesses and stores. A critical characteristic of the revolution was the beginning of the investors. Investors placed their money in the process and were interested to know how valuable the money invested could become. It was the beginning of the productivity definition from professor Sink in Figure 4 further in this document.

The term became popular in North America after the fifties and sixties, and even the U.S. government sponsored a conference exclusively about the topic. The conference Productivity Growth: A Better Life for America (White House Conference on Productivity (1983: Washington, 1984) attests the productivity importance in the first sentence of the Executive Summary: *“The Challenge of greater productivity is of supreme importance to America’s future.”* The rapport defends, in 1984, the challenge caused by poor management and work practices. Also, by the neglect of quality and cooperation in the workplace. All these topics are still in the discussion today. In his famous book Productivity Management, Professor Scott Sink (1985) describes productivity as the rate of output and inputs.

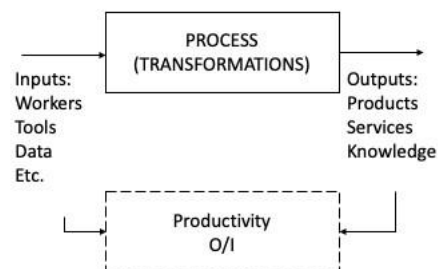


Figure 2.1 Basic concept of productivity (Source: Sink, 1985)

The author defines productivity as the necessary time to solve a problem in this work. The input is the number of problems in the company, and the output is the number of problems by hour solved. With this definition, the work will compare the relation between productivity, the time planned to solve a problem, and the real-time needed to solve it.

Productivity is also measured by their growth. Not just the rate between the output and input but the behavior of the rate along the time. The managers can ask: *“Is this sector, company, city, or nation becoming more productive over time?”*

Several researchers (Greasley, 2009; Sink, 1985; Sink & Tuttle, 1989) agree with the basic productivity points as the table below describes.

Table 2.1 Productivity Main Features

Number	Term	Meaning
1	Input Variable	Any controllable factor or resource available in the first activity of the process
2	Process	An additional value to the actual value of the product or service
3	Output variable	Any controllable factor or resource available the after the last activity of the process
4	Outcome variable	The result or value of the output
5	Attribute	An identification characteristic of a variable. (size, color, etc)
6	Measure	The development of indicators (KPI's) in the process
7	Productivity Measurement	Ratio of output measures to input measures

As defined later in chapter 3- Methodology, this table directly inspires some of the variables defined in the model.

Productivity is a topic still on the agenda today. There are at least twenty conferences worldwide just in 2021 with productivity in the keywords or on the title. The conferences are spread between several areas: health, engineering, consulting, economics, business, and services are just some of the topics.

However, even with the subject is in high demand, productivity is still in decay, as shown in the previous chapter. There are important points related to the decay of productivity. Some of these points are:

1 - Lack of the right tools.

The employee wastes time searching for the right tool, and if she does not find the right one, she will improvise with another similar one. This waste of time reduces the engagement and the quality of the work performed.

2 - Lack of wrong feedback.

Feedback is the opportunity to guide the employee through her career growth, showing clear objectives, and constructive feedback motivates the employees to progress. She will know what to do and if it aligns with the company's objectives.

3 - No perspective or progress on the employee path.

Like the previous point, the employee will naturally reduce her productivity when she realizes that her work has no apparent value or her effort is not valorized by the company.

Productivity and continuous improvement have their roots in the same place. Due to the basic objective of a continuous improvement project, reduce of waste, reduce errors, and reduce work overload (as explained in the begging of the introduction) the natural result of a project is the increment in the productivity (Reid, Richard A., 2006)

Furthermore, engagement is related to productivity, according to dr. Sink and Dr. Tuttle (1989), engagement is an intervention necessary to control and improve productivity. The next topic explores the bases of employee engagement and its relationship with productivity.

2.2 The Employee Engagement and Continuous Improvement relation

EE is not a new idea. The topic has been discussed for a long time, and it has had a substantial impact on the economy. The company Gallup, founded in 1935, and known by its public opinion polls conducted worldwide, also provides a survey to measure the EE. Q12 is a survey with twelve (12) questions applied to the employees, in a volunteering way and anonymously. The objective of this survey is to measure employee engagement.

This is one example of the EE classic method. Nevertheless, before diving more profound into the methodologies available is essential to understand what engagement is. The next topic will explain it better.

As identified in the introduction, the topic of employee engagement is not deeply researched in academia. However, the lack of academic papers about the topic, the importance is discussed daily by many Human Resources departments. Related to employee engagement, and previously researched in academia, is the concept of “Burn-out.” Dr. Freudenberger published an article related to the topic in 1974 (Freudenberger, 1974). The article “Staff Burn-out” was a pioneer in the area, bringing importance to the topic in the healthcare area. Just after Dr. Freudenberger, in 1976, a significant paper was also published. With the simple title “Burned-out” (Maslach, 1976), Dr. Christina Maslach shed much light on an important topic: The psychological state of the employees. It was the predecessor of employee engagement. And before measuring it, these articles focus on identifying and understanding a behavior.

After some years, the research transitioned to a more positive approach: employee engagement. To cite just two, important authors such as Dr. Christina Maslach and Dr. Wilmar B Schaufeli guided this movement. William A. Kahn (1990) was one of the pioneers to publish about engagement. Corresponding to Maslach, the psychological view of engagement is the article’s focus. The balance between data generation, data analysis, and understanding of the literature is present in the article. Also, like Maslach, the data is qualitative. The data is formed from interviews, observation, and document analysis. This article presents one of the first definitions and examples of employee engagement.

In his article, Dr. Kahn cites an example from a summer camp (one subject of his study) where the scuba-diver professor dedicates more time, skills, and knowledge to the students than requested by the employer. It means an engaged employee will do more than the minimum required. To Kahn, employee engagement englobes personal presence and connection in three areas: (1) Physical: Be present, participate, and collaborate. (2) Cognitive: The process of the brain to learn, have perception, memory, problem-solving, and creativity. Furthermore, (3) Emotional: What do you feel about your work?

Dr. Kahn also interviewed the employees in the second research site analyzed in the article. The author conducted the interviews and asked the employee to recall four different situations where they had felt:

1. alert, absorbed, or involved in their work;
2. uninvolved, detached, or distracted from their work;

3. like acting differently from what he/she believed he/she would respond if they had not been at work; and
4. that there were no differences in their behavior in how they believed they would react.

After the author analyzed how many were engaged and how many were disengaged. Consequently, the article was a mark in the engagement research measuring the engagement level in the company. Although it is still more related to the psychological aspect of the engagement, the work identifies specific areas where the companies can work to preserve the “psychological safety” of the employee, such as work interaction and interpersonal relations, the management style and process, and the organizational norms.

Different authors defend the EE’s importance and bond with several companies’ key indicators over the last 20 years. The authors Miscikowski and Stein (2006) compared the key indicators of eight thousand business units to find a link between the EE and the other enterprise’s indicators, including profit. Their article concludes the meaningful relationship between the business outcome and the EE.

The authors J. K. Harter, Schmidt, and Hayes (2002) wrote two articles about EE’s positive points, retention, productivity, financial return, and even employee work-related accident reduction. Other authors, such as S. Markos and M. Sridevi (2010), also support the EE’s importance in increasing performance. They defend: “Employee engagement is (a) stronger predictor of positive organizational performance.” Also, Gruman and Saks (2011) reinforce EE’s importance and proposed a model to foster high performance. They suggest the use of the EE variables and ideas to increase job performance. Linda Holbeche, in 2012 (Holbeche & Matthews, 2012), wrote a book where she summarized: “A praise for engagement. An easy-to-use guide to employee management offers real solutions for getting workers engaged and increasing productivity.”

And finally, Michael P. Leiter and Arnold B. Bakker are some of the prominent authors focused on EE, or work engagement, as explained in their book: *Work Engagement - A handbook* (Bakker & Leiter, 2015). According to their definition, the importance of EE is:

“Work engagement has far-reaching implications for employees’ performance. The energy and focus inherent in work engagement allow employees to bring their full potential to the job. This energetic focus enhances the quality of their core work responsibilities. They have the capacity and the motivation to concentrate exclusively on the task at hand.”(p.3)

One vital point to measure and increase EE is its proper definition (Bakker & Leiter, 2015). EE has received several and sometimes contradictory explanations. Some examples are detailed below. One of the newest definitions found during the literature review is provided by (Saks A, 2017):

“Involves a holistic investment of the entire self, focuses on work performed on a job, and involves a willingness to dedicate physical, cognitive, and emotional resources to one’s job.” (p.78)

Saks based his definition on one of the pioneer definitions of engagement, provided by Kahn in 1990. The Kahn definition is:

“The harnessing of organizational members selves to their work roles and employing and expressing oneself physically, cognitively, and emotionally during role performances.” (Saks, 2006) (p.601)

Saks also split the engagement definition into academic and practitioner research. Companies such as Gallup Inc., also defined the engagement:

Interpret the Gallup Engagement Index as measuring *“How each employee connects with your company and with your customers.”* (p12). They call the opposite of this state: “Emotionally unemployed.” (Gallup, 2017)

This work also lists other academic definitions to sum with Saks and Kahn. Just below, Robinson, Perryman, and Hayday (2004) define engagement in their paper called “The drivers of employee engagement” as:

“A positive attitude held by the employee towards the organization and its values. An engaged employee is aware of the business context, works with colleagues to improve performance within the job for the benefit of the organization. The organization must develop and nurture engagement, which is a two-way relationship between employer and employee.” (p.2)

M. Attridge (2009) engagement definition is:

“Work engagement has since been defined more completely as when employees feel positive emotions toward their work, find their work to be personally meaningful, consider their workload to be manageable, and have hope about the future of their work.” (p.384)

And finally, Professor Rich (2010) definition is:

“A multidimensional motivational concept reflecting the simultaneous investment of an individual’s physical, cognitive, and emotional energy in active, full work performance.” (p.01)

This work also aims to define engagement based on the references above and previous experiences acquired during the authors’ academic and professional knowledge.

The objective is not to sum up another definition, but to align the definition with this work’s purposes. In this way, the engagement definition to guide this work is:

“An engaged employee is the one who desires the growth of the company as a whole. He/she dedicates the working hours not just to achieving the individual goals with excellence but also to searching for improvement opportunities to support the organization’s mission and vision.”

The tool proposed in this work has the goal aligned with this engagement definition:

“Help the companies to identify the amount of CI time necessary to reduce the number of problems in the process and measure employee engagement during the project.”

As cited before, Graban (2016) published a book called: “Lean Hospitals - Improving Quality, Patient Safety, and Employee Engagement.” In the introduction, the author relates the importance of small kaizens to engage the employees. In chapter 11, Graban and Toussaint explain how some CI tools can support a higher EE. In 2018, Browall and Canacari Maurer published two articles defending the relationship between a daily management system CI methodology and the advance of employee engagement. It can empower staff to identify problems and provide the right environment for them to work together to solve these problems. The last article cited in this work is about the relationship between CI and EE was published by Morton, Roca, and Wagner (2019). In her article, she proposes nine hypotheses to increase the EE, and once the employees achieve an EE higher level, the CI project will also earn higher success. The authors offer individual and team effort empowerment, creative activities, and transition in the hypotheses’ management styles.

Although the articles cited provide a strong base to compare the CI methodology variables with EE’s variables, the author of this work did not find in their literature review a method similar to the one proposed in this article. Founded on the previous examples, the next paragraphs of this work detail the existing methodologies to measure employee engagement.

Since the beginning of the studies on employee burn-out, with Dr. Christina Maslach and Dr. Jackson, models for measuring the psychological impact or event of burn-out in employees were

developed. Dr. Maslach and Jackson published the first idea about the measurement of psychological behavior, in that case, the measurement of the burn-out, in 1981 with the article “The measurement of experienced burn-out” (Maslach & Jackson, 1981).

In that article, the authors suggested a scale to measure the burn-out experienced by the employees. Based on the authors’ experiences and previous publications, the first scale to measure employee burn-out was focused on the “people-work,” which means areas where the relationship between the employee and patient happens. In the article by Cropanzano and Mitchell (2005), the authors used several previous interviews. They analyzed hundreds of answers from a survey with twenty-six questions and two levels of answer, frequency, and intensity. Maslach and Jackson compared the results with previous research and hypothesis, providing a long and pertinent discussion about the burn-out, satisfaction, and engagement. Based on the articles cited before and in the EE tools available online from the companies and authors who proposed it, the table below summarizes some of the main variables in the EE surveys.

Table 2.2 Employee Engagement and CI variables

EE Tool	Variable also present in CI
SET	Reciprocity, altruism, and group gain
UWES-17	Clear objective and purpose, Challenge, opportunities to try
Q12- Gallup	Objective, feedback, empowerment, group gain, learning opportunities
Aon	Collaboration, empowerment, autonomy, Learning, management collaboration
Towers Watson	Goal and objectives, Empowerment, Communication, Leadership

Influenced by these first results and methodologies, several companies started researching and selling tools to measure employee engagement. Gallup Inc., departed a research mission to develop a tool able to measure employee engagement. In 1996 they provided the Q12 employee engagement survey, a survey with twelve questions where the employees can answer their personal inclination, or agreement, between one to five, to several points related to employee engagement, satisfaction, and personal relations at work. Nowadays, more research is performed by companies, exploring the data from the clients who bought the survey, than academic research. The table below shows

the measures of three companies that measure employee engagement. Gallup, in his 2020 report, BlessingWhite with his 2013 report⁶ and Tower Watson with his 2014 report⁷:

Table 2.3 Employee Engagement Level

	Disengaged	Moderately Engaged	Actively Engaged
(2020) Gallup Organization (U.S.A)	20%	54%	26%
(2013) BlessingWhite (North America)	15%	45%	40%
(2014) Tower Watson (Worldwide)	24%	36%	40%

The table shows how representative the moderately engaged is. In the Gallup report, the middle group represents more than 50%. Only in the Tower Watson report is it possible to see a majority formed by actively engaged employees.

The two first models, about productivity and employee engagement, use the Lotka-Volterra model as inspiration and base. The third model uses another tool for the simulation: A multi-agent system. The following section explains the bases of the third model.

2.3 How continuous improvement is related to participatory management

According to Rensis Likert, in his book “Developing Patterns of Management,”: Participatory management (PM) is one of the four management styles, together with *Exploitative Authoritative*, *Benevolent Authoritative*, and *Consultative*. It is characterized as a style under which “Managers have complete trust in subordinates, and much of the decision making is accomplished by group participation.” Underlying this style is the belief that employees may reach their higher potential through participation. Also, morale and satisfaction are increased, and resistance to change decreases. Improved performance is not a direct result of participation. Instead, it results from the

⁶ <https://blessingwhite.com/wp-content/uploads/2018/11/Employee-Engagement-Research-Report-2013.pdf>

⁷ <https://www.wtwco.com/en-US/Insights/2014/10/global-trends-in-employee-attraction-retention-and-engagement>

fact that participation positively affects the satisfaction and motivation level of the employees who participate (Lichtenstein A, 2000). Participatory management has different features and dimensions (Coye RW, 1995). The author will focus on four features of PM: Collective intelligence, communities of practice, idea flow, and social pressure. These four points do not completely cover the PMs' features but are a strong introduction and reference for the model presented in this work. Also, this work proposes the relationship between the continuous improvement project and participatory management. As defended during the introduction and deeper explained in the methodology, the CIP has the characteristics to simulate the social variables, including participatory management. Landry and Beaulieu (2021) indicate the collective intelligence of a CIP when a group of employees works together to improve a process. The communities of practice are a standard part of a CIP. The following paragraphs will detail these points.

2.3.1 Collective Intelligence

Collective intelligence is defined by a group's simultaneous, collaborative work with the same objective. This group could be the predators working together to hunt prey, a team of employees from different sectors working on the same continuous improvement project, or a global peer review for a science project (Suran, 2020). The potential to achieve with participatory management simulation and collective intelligence is promissory. Several studies were performed to understand the importance of collective intelligence simulation (Senge P, 1990, Watts D, Strogatz S, 1998 and 2011; Noriega-Campero A, Almaatouq A, 2018 and Suran, 2020). Surowieck, in his article from 2004, explores collective intelligence in four areas, as identified below:

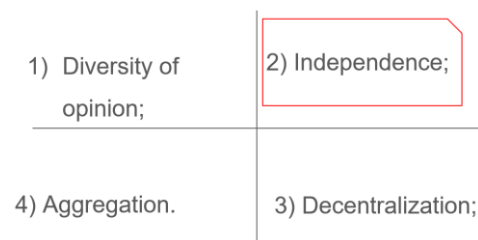


Figure 2.2 Collective intelligence (Source: Surowieck, 2004)

The division into four blocks represented the main parts of a collective intelligence implementation. The first part is the “Diversity of opinion,” where each person should have private information even if it is just an eccentric interpretation of the known facts. The second is “Independence,” (the

author Surowieck focus on this topic; therefore it is highlighted here) where the opinions of those around them do not determine the people's opinions. Also important is decentralization - People can specialize and draw on local knowledge. The last part is aggregation, which means "Some mechanism exists for turning private judgments into a collective decision." Collective intelligence based on empowerment is participatory management.

2.3.2 Communities of practice

A critical point, together with collective intelligence, is the term coined "community of practice." A community of practice is an organized group in a company, in a city, or between any group with no direct relationship. The objective of this group is to discuss, review and learn any topic of interest to the group. As the name declares, the group's objective is not just to learn in a classroom but to practice. It is a training opportunity, sometimes formal, as developed in a company, or sometimes self-generated as among a group of friends with no clear leader or curriculum.

Etienne Wenger well defines the term in his Cambridge University Press from 1998: "Communities of practice are formed by people who engage in the process of collective learning in a shared domain of human endeavor: a tribe learning to survive, a band of artists seeking new forms of expression, a group of engineers working on similar problems, a clique of pupils defining their identity in the school, a network of surgeons exploring novel techniques, a gathering of first-time managers helping each other cope. In a nutshell: Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly."

2.3.3 Idea flow

Alex Pentland introduced the term "idea flow" in his book "Social Physics" in 2015. The idea introduces a methodology to measure an idea's physical movement. Although this new theory from Pentlands is a mark in the idea flow literature, the social physics area started during the '50s with the John Stewart publication "The Development of Social Physics" (Stewart J, 1950). In this paper, dr. Stewart defined the first steps of a methodology to measure social physics.

To understand the term "idea flow," the term "social physics" must be reviewed briefly. The idea is to use mathematical methods to measure human behavior with big data: Data from social media,

credit cards, or GPS. Inspired by this methodology, Pentland proposed his tool to measure the idea flow in a company.

It is important to remark that the methodology does not record all the ideas or follow it as a GPS in a car. The idea flow is a series of measures of participation, interaction, and even the number of ideas proposed in a company by its group of employees. There is an intrinsic relation between continuous improvement and participatory management. Once the idea flow and the interaction between the group participants start to be measured, the leaders of this initiative can better understand the problems and propose even better ideas.

2.3.4 Social pressure

The last side of participatory management presented is called social pressure. Differently from the last topic, social pressure is not a methodology to implement, but it impacts participatory management. Social pressure, also called peer pressure, can even change companies, as defended by Chirstopher M (2016). It can happen on the most straightforward occasion as seeing a neighbor start to recycle or, in the case of participatory management, seeing a peer engaged in a continuous improvement project. Although the opposing view and harmful application and side effects, social pressure can also include rational arguments, persuasion, conformity, and demands.

The following two sections will focus on the tools chosen for the simulation. The first two propositions, productivity and employee engagement, use the Lotka-Volterra system of equations as inspiration, and it is the first tool used. Furthermore, the third proposition, participatory management, uses the multi-agent system as a tool to model the proposition. After reviewing these tools, the author shares alternatives for the tools selected and discusses why the two tools were chosen.

2.4 Lotka-Volterra model

In chapter 1, the model Lotka – Volterra was introduced. This model was selected because of its characteristic of *balance* between populations. In the LV model, the populations are the (1) predators and the (2) prey and compared with a CIP project, the populations are (1) the time spent on continuous improvement and (2) the manufacturing problems.

The LV model is also known as the predator-prey model. The predator-prey model is a biological-mathematical model that explains the relationship between two or more species competing for a common resource. The model explores the population dynamics and classifies it into three types of interaction: (1) If the growth rate of one population decreases and the other increased, the populations are in a predator-prey situation. (2) If each population's growth rate decreases, it is competition. (3) If each population's growth rate is enhanced, it is called mutualism or symbiosis.

Volterra (1926) first proposed a simple model for predating one species by another to explain the oscillatory levels of certain fish catches in the Adriatic ocean. If $H(t)$ is the prey population and $P(t)$ that of the predator at the time "t," then Volterra's model is:

$$\frac{dH}{dt} = Hr - aHP$$

$$\frac{dP}{dt} = -Pm + bPH,$$

Equation 1 Lotka-Volterra Main Equation (Volterra, 1926 and Murray, 2002)

$H = H(t)$ Number of preys

$r > 0$ Birth rate of prey

$P = P(t)$ Number of predators

$m > 0$ Death rate of predators

$a > 0$ Death rate of prey/predators

$b > 0$ Birth rate of predators/prey

The model assumptions are:

(1) The prey will grow without bounders if there is no predator, moral restraint, or disaster (such as a disease, famine, or war) happens. However, widespread poverty and degradation are inevitable.

HP represents this challenge;

(2) The predator effect is to reduce the prey growth rate. The growth is Hr term;

(3) Without enough prey, the predator death rate will exponentially increase. Represented by the $-Pm$;

(4) The prey impact on the predator's growth rate by the -aHP. This aspect balances the size of the prey and predator population.

Another important Lotka-Volterra characteristic is the wide use in similar areas. This biology math theory has been used in different areas, such as the economy, engineering (Zangwill & Kantor, 2000), or even climate change impact (S Jeon, 2016). The first author to use the LV equations in a different area was Richard M. Goodwin's "Goodwin model" in the paper: "A Growth Cycle" from 1967. Goodwin was the first to compare the cyclical behavior from LV equations and economic growth (L Weber, 2005).

Zangwill worked with the learning curve and the LV equation to understand the learning process in a company based on management effectiveness. This understanding was possible by applying his "learning curve differential equation." Similar to the work of Zangwill (2000), this work aims to compare predator and prey with the continuous improvement methodology. However, focusing the interaction between workers on solving the problems and the manufacturing problems.

As said before, the balance between populations is the main point of the LV model for this project. The figure below shows this balance.

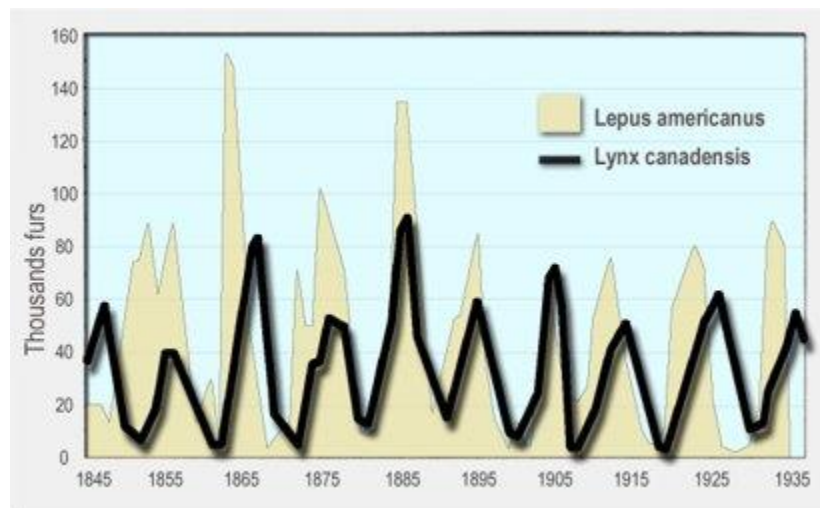


Figure 2.3 LV Equilibrium (Source: Pilovsky et al. 2001)

In the figure from the book "Synchronization: A universal concept in Nonlinear Sciences," the authors show how abundant the balance is in science, nature, engineering, and social science. The picture shows the comparison between *Lepus americanus* and *Lynx Canadensis* over 90 years. The

equilibrium portrayed in this picture is the equilibrium aim by the author during a continuous improvement project.

This equilibrium is based on the hypothesis that the time dedicated to continuous improvement will reduce the number of problems. Once the number of problems decays, the total hours of continuous improvement will also decay. This decay will increase the total of problems, forcing the continuous improvement hours to increase again. Figure 5 shows the causal loop diagram for this equilibrium.

A *causal loop diagram* is a tool inspired by the system dynamics model (as said in the previous section). The most significant advantage of this tool is the visualization of how different variables, agents, or rates are interrelated. The diagram is a set of arrows, loops, and intersections. In the case below, the intersection represents the agents: Prey and Predators. Also, the death rate and the growth rate. The positive signal represents the kind of influence on the next agent. For example, the prey growth rate influences the number of predators. The figure below shows the causal loop and the dependence between the variable in the classical model.

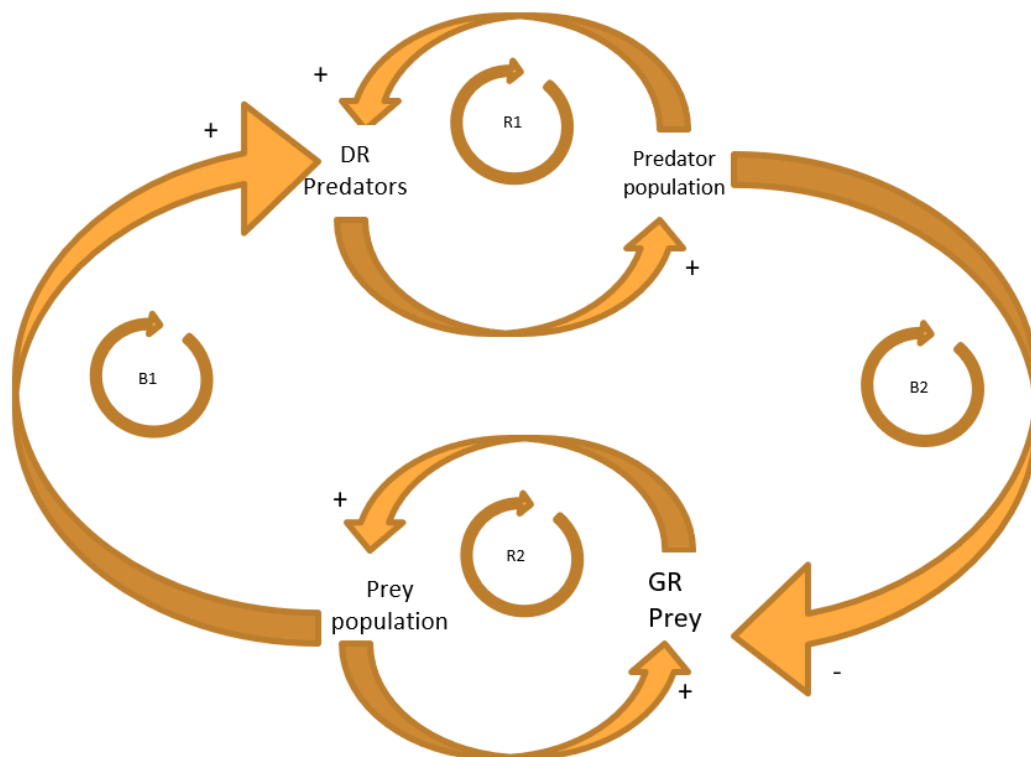


Figure 2.4 Causal loop diagram Lotka-Volterra model (Source: The author)

Meanings: DR = Death Rate Predators

GR = Growth Rate Prey

B1 or 2 = Balancing loop

R1 or 2 = Reinforcing loops

There are two main reinforcing loops. The Predator quantity depends on the number of prey and its death rate. The number of predator changes with the growth rate, which in turn, depends on the number of preys. The balancing loop creates oscillations in the model.

The chapter 3 – Methodology, shows the adapted Causal Loop Diagram and explains the relation and differences between the models.

As enunciated previously, this relation is only found in the Lotka-Volterra model, which is why the author chose to use this model as inspiration. The Lotka-Volterra is still the main inspiration for the third model, participatory management. However, the author tested the Multi-agent system simulation and not solve the nonlinear equations with a numerical method as realized for the first tool, productivity.

2.5 Multi-Agent Systems Simulation

The third tool presented in this work uses the multi-agent system simulation instead the Lotka-Volterra model. Before presenting the tools, this section will build the foundation for the MASS literature, and the next section will explain why these two tools were chosen. The concept of agent system stems from the lexicon of distributed artificial intelligence (DAI) popular in the 1970s. Since there, researchers have applied agent-based models or multi-agent systems in different areas, from economics and social interaction to medicine and statistics. However, especially in the automation and manufacturing domains (S Jeon et al, 2016). The figure below presents the main characteristics of multi-agent systems.

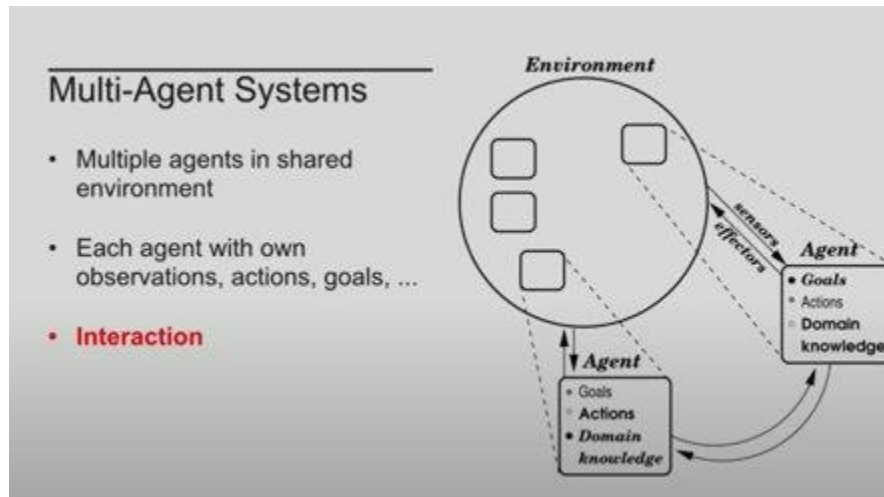


Figure 2.5 Multi-agent system characteristics (Source: Schäfer, L & Albrecht, S, 2019)

Multi-agent systems are the interaction of agents in the same simulation. It is formed by a system of computational agents that cooperate and typically communicate with each other. This communication changes the model and can act as a trigger to develop the simulation. An agent can represent physical resources (machine tools, robots, automated guided vehicles, and products), logical objects (schedules and orders), or statistical order to manipulate a database. Using properly distributed control algorithms, individual machines and product agent can create their manufacturing control choices related to resource allocation and coordination by using an automated form of negotiation.

The most significant advantage of a multi-agent system simulation is that the cooperation process still occurs if the production is disrupted in some ways. Due to its ability to make decisions with different machines, the system is relatively robust to change over time (S Jeon, 2016; P Leitao, 2009).

One part of the multi-agent simulation is based on system dynamics. MIT professor Jay Forrester in the 1950s was the first to introduce System Dynamics. His first role was to investigate and describe economic and social systems dynamics in companies like General Electric. Based on his science and engineering background, he developed the system dynamics approach. One of the System dynamic's advantages is the high speed of identifying feedback loops and can include them in the model (S Jeon, 2016). The causal loop diagram is one part of the system dynamics. This visualization tool is explored in the next section to explain the balance in the Lotka-Volterra model.

2.6 Alternatives for the proposed models

Although this work cites the Lotka-Volterra model as its main inspiration for the models proposed here, the LV model is nothing more than a system of Nonlinear equations. The two most famous nonlinear systems of equations are the Lotka-Volterra, extensively cited in this work, and the Navier-Stokes equations. The Navier-Stokes equations describe the motion of viscous fluid substances.

Even though both systems (Lotka-Volterra in biology and Navier-Stokes in physics) are nonlinear equations, their functions and objective are very distinct. LV is adapted chiefly for economics and management, and NS is adapted mainly for water/air flow, weather, and ocean currents. There are three versions of the Lotka -Volterra model: The general or simplified model, the competitive model, and the model with N number of species. The author uses the general model due the reasons below:

- (1) The general model has the same characteristics as the hypothesis, which makes the comparison between problems and prey possible. Compared with the hypothesis, the employees are not competing with the problems.
- (2) The nature of the LK equations, with its equilibrium between populations. The nature and bases of the model are closer to the continuous improvement reality than the NS equations.
- (3) For the continuity of other works, like Zangwill and Kantor, the author of this work decided to adapt the LK equation.

Apart from the nonlinear systems, there are other mathematical or statistical models as an alternative to this research. These alternatives can counterattack one characteristic of a Nonlinear system of equations: It is characteristic that a change in the input is not proportional to the change in the output (MDPI AG., 2021). The discussion chapter addresses this point more.

One system of equations that searches the equilibrium of its variables is the "Demand and Supply model." This model aims to answer questions like: "How many pizzas will people eat this year? How many doctor visits will people make? How many houses will people buy?"

To answer these questions, economists will analyze the (1) quantity demanded, which means the quantity needed, the (2) quantity supplied, which means the quantity sellers are willing to sell at a particular price during a particular period, and all other things unchanged.

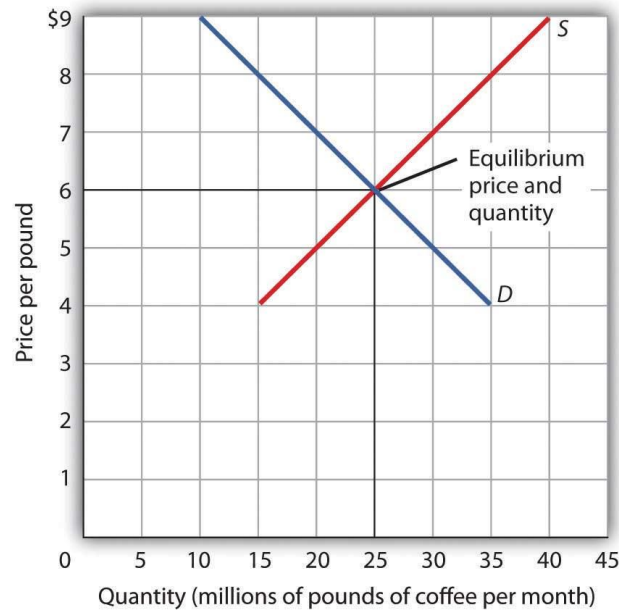


Figure 2.6 Determination of price and quantity (Source: Principles of Economics – University of Minnesota)

It is possible to create a demand and supply model based on these two variables. The users of this model can analyze the curves and explain the determination of price and quantity in a market. The figure above shows this equilibrium. The equilibrium is between the price per pound the consumers are willing to pay (the demand) and the quantity the producers are willing to produce (the supply). In this example, the equilibrium price is \$6 per pound. Consumers demand, and suppliers supply 25 million pounds of coffee per month at this price (Principles of Macroeconomics, 2016). This equilibrium could be used to balance the problems and the time of continuous improvement, as the author proposes with the Lotka-Volterra model. One advantage of the LV model is the balance over time, not at a specific point as the Demand and Supply model suggests.

Other tools can be used to simulate the scenarios proposed in this work. One is multi-agent system simulation, used for the third model, and machine learning techniques. The table below shows the pros and cons of each tool.

Table 2.4 Alternative's pros and cons (Source: The author)

	Pros	Cons
Lotka-Volterra	1 Number of variables fit with the variables present in CIP; 2 The natural balance of the model fits with the CIP; 3 Extensive research in social science with this model; 4 Previous research of Zangwill and Kantor.	1 The chaotic behavior of a nonlinear equation.
Demand and Supply model	1 The model presents a natural equilibrium; 2 Simple to adapt and simulate	1 The number of variables in the model does not fit with the number of variables in a CIP; 2 The hypothesis proposed in this work does not fit with the basic proposition of the model; 3 No related previous research between the two topics.
Multi-agent System	1 Eliminates the chaotic behavior of nonlinear equations.	1 Complex to code and simulate;
Machine Learning	1 Eliminates the chaotic behavior of nonlinear equations.	1 Complex to code and simulate; 2 Requires a significant quantity of data.

2.7 Conclusion

The previous sections and paragraphs review the main points about continuous improvement, productivity, engagement, and participatory management. Also, the bases for the tools chosen in this work. The Lotka-Volterra equations and the Multi-agent systems. These six parts are the pillars of this work.

Continuous improvement is the methodology to solve problems and the main point of this work. This methodology can provide the variables needed to measure and increase productivity and employee engagement and place the bases of participatory management. Productivity can be defined as producing a good or a service with excellence and fast. Engagement is a psychological aspect that increases the personal capacity of work, and participatory management is the methodology for embarking the whole hierarchy in the management decisions. Based on the study of collective intelligence, communities of practice, idea flow, and social pressure, managers can better use the front level (the shop floor) to help make decisions.

It was possible to see the history, importance, and relation between the six main parts of this work in the literature review. The bases of continuous improvement are similar to productivity, employee engagement, and participatory management. The following section, Methodology, will present these links.

The variable of continuous improvement firstly inspired this work. Based on these variables, the author searched the relation between productivity, employee engagement, and participatory management. The following chapter, methodology, will discuss these relations more.

CHAPTER 3 METHODOLOGY

The methodology chapter explores how to answer the questions proposed previously. The chapter introduces the models and explains how to test them. The chapter starts with a central methodology, unique for the three models, and later a specific methodology for each model. The chapter finishes with a conclusion.

3.1 Research Objectives

The previous chapter covered the literature review of the four subjects present in this work: Continuous improvement, productivity, employee engagement, and participatory management. It also explains the tools used to perform the simulations: The Lotka-Volterra model and the multi-agent systems.

These two tools are tested to verify their applicability and capacity to simulate social physics variables. Although the tools are well established in their respective areas, biology to Lotka-Volterra and manufacturing simulation to multi-agent system, the author aims to merge the areas and the tool to find better solutions to the classic methods. As explained in the introduction and literature review, the variables explored in this work have their measurement methodology. Employee engagement, for example, has questionnaires and surveys distributed to measure a motionless level of engagement. The hypothesis of this work defends that an adaptation of the Lotka-Volterra and the Multi-agent systems can provide better ways to measure the variables proposed.

This chapter shows the methodology implemented to reach the objectives of this work. As cited before in the chapter introduction, this work aims *to find a relation between the continuous improvement project and social variables*. To reach this objective, the author proposes four sub-objectives:

- 1 - Propose an adapted Lotka-Volterra model able to measure productivity, employee engagement, and participatory management;
- 2 - Test the adapted model with the data of a continuous improvement project;
- 3 - Explore the relationship between the CIP and the three areas previously proposed, comparing the equilibrium of the adapted Lotka-Volterra model;

4 - Explore the problems and discusses how the adapted model proposes a valid alternative. Chapter 5 (Discussion) will address these objectives.

3.2 Central Methodology

This work proposes a central methodology to fulfill the objective previously cited. This methodology is the base for the three models proposed here. For this reason, although with a few differences, the central methodology guides all the others. The figure below draws the main points of the methodology.

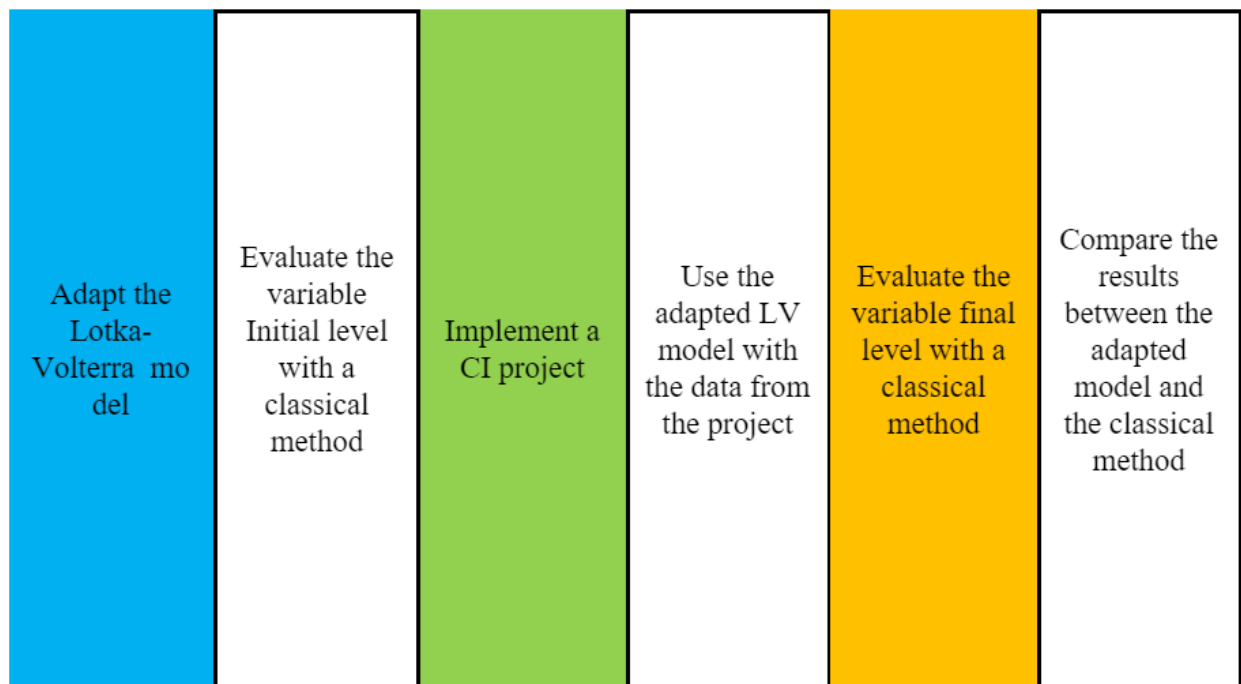


Figure 3.1 Central methodology for the work (Source: The author)

The methodology is inspired by the scientific method. The author proposes new ways to measure a variable. The results are compared with a classical method to calibrate and validate this proposition. The first step, not identified in the figure above, is to define the Lotka-Volterra as the new tool to measure the social variable. With this definition, the methodology passes through 6 steps.

(1) Adapt the classical method to consider the data from a continuous improvement project. (2) Evaluate the initial level with the classical method. For example, the Gallup Q12 (cited in the Literature Review) measures employee engagement's actual level. (3) Implement a CIP. The

project will provide the data. The data and the opportunity to train the participants in the topic studied. When using the first tool to measure productivity, the managers can implement a CIP and train the employees on the correct view of productivity. (4) During the project, the responsible collect the data to use in the adapted model. (5 and 6) The responsible also performs a second measure with the classical method, then compares the results from the adapted model with the classical method.

The ensuing sections will explain in more detail the methodology of each tool, but first, the author will detail each adapted model.

3.3 First tool - Lotka-Volterra model adaptation

As introduced before, the project will adapt the LV model. Zangwill and Kantor performed a similar adaptation (1998, 2000) when they explored the Lotka-Volterra Model as an opportunity to understand and complement the learning curve. Zangwill and Kantor compare the problems as "prey" and the management as the predators.

Although similar to the present work, the innovation introduced by this first adaptation is a method to define how much time my team needs to dedicate to continuous improvement. By doing so, the work proposes a tool to design the CI team. Furthermore, the manager can find an answer to the question: "How many hours do workers need to participate in this project?"

The proposed model is:

$$dpb/dt = GR. pb - s.w.pb$$

Equation 2 Derivative of problems along the time (Source: The author)

$$dw/dt = -DR. w + c.pb.w$$

Equation 3 Derivative of workers along the time (Source: The author)

In an analogy to equation 1, where the difference between Hr and aHP defines the derivative of preys H, the derivative of problems (pb) in equation 2 is defined by the difference between the problems' growth rate (GR) and the constant success rate (S). The constant (S) multiplies the time dedicated to the problems (Pb) and the continuous improvement actions (Workers - Wk) at the

moment analyzed. The problems have a growth rate. It means that the problems naturally increase when there are no actions or the worker's rate decreases.

A similar analogy is established between the second part of equation 1 and equation 3. In this case, the derivative of predators (P) is evaluated by the sum of $-P_m$ and bPH . Nevertheless, the derivative of workers (w) is evaluated with the workers' death rate (DR) plus the constant communication (C). This constant (C) multiplies the time of problems and the time of CI (workers) at the moment analyzed.

For a definition of "problem," the authors propose the following:

"The difference between the time expected (the goal) and the real-time, when the second is higher."

For example: If the objective is to finish an activity in 3 hours and the employee, for any reason, took 5 hours, these two overtime hours (or waste time) are included in the variable "problem." In the same way, the definition of "workers" is the time dedicated to continuous improvement by the employees. It could be an individual effort, a group-managed, or a control effort. Both variables, the problem, and the workers, are always measured as groups and not by an individual worker. The relation between the prey and the problems is one of the main points of the work's hypothesis. This relation presents some limitations, as section 5.2 will discuss in more detail.

The "Growth Rate" (GR) is the rate related to the natural increment of the problems. Once the CI actions stop or reduce, problems will naturally increase. This variable is inspired by the growth rate of the prey in the original LV model. The "Death Rate" (DR) assumes the same approach. The DR is related to the natural reduction of continuous improvement dedication. It (the CI time) could certainly reduce if there is no continuous improvement effort by the management. Observing the reduction is why this variable has incorporated the nature of the "Death Rate," inspired by the predator death rate in the original model.

The "Communication" (C) and the "Success fee" (S) are the interrelation factor between problems and continuous improvement actions. If $S = 0$, the company has no new problems Showing up during their operations. More prominent is the "S" more capacity to create problems the company has. The $C = 0$ means a CI team non-functional. "C" represents the organization's trust factor in the continuous improvement team. The CI team's capacity to focus on the actual problem. In this context, defining the variables used in the model is essential. The figure below compares the new variables with the variables used in the classical model.

Table 3.1 Relation between the variables

Variables List		
Definition	Variable in the adapted model	Variable in the classical model
Derivative of problems	dpb/dt	$\frac{dH}{dt}$
Growth Rate	GR	r
Problems	pb	H
Success fee	S	a
Derivative of CI time	dw/dt	$\frac{dP}{dt}$
Workers (CI time)	w	P
Death Rate	DR	m
Communication	C	b

To help understand the adapted model and follow the same explanation of the classical method, the figure below shows the causal loop for the model adapted model. There are two main reinforcing loops. The problem quantity depends on the problem's growth rate. The number of workers changes with the death rate, which depends on the number of problems. The balancing loop creates oscillations in the model.

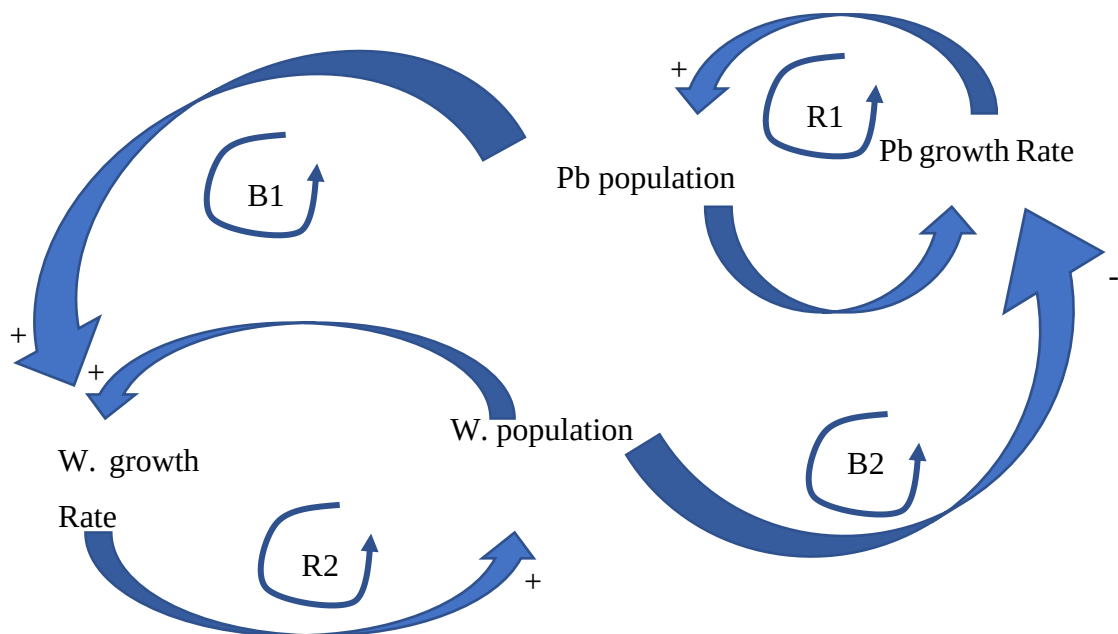


Figure 3.2 Causal loop of the first tool (Source: The author)

Meanings: Pb = Problems

W. = Workers

B1 or 2 = Balancing loop

R1 or 2 = Reinforcing loops

These equations can help answer two questions: (1) At what rate are the problems growing up in the company? (2) How many CI hours does the manager need to reduce the time of problems?

With the model proposed in this work, it is possible to analyze the balance between the problems and the time dedicated to CI. Based on this model, this work proposes the following applications:

- Previous planning of the Continuous improvement team;
- Simulate the number of hours necessary to reduce the problems to a previously defined goal;
- Definition of the problem goal. According to the number of employees and hours available.

The authors also identify some limitations to the work and the model:

- The simplicity of the model;
- The mode consider a general problem and a general CI application, but the reality of any process is complex;
- The model demands specific data available before the project starts. This data is not always available;

The next section explains the operation behind the mathematical model. How code works and the details of the inputs and outputs of the model. The code and the database used in this work are available by request to the author.

3.3.1 Simulation model and database

To solve the model, the author used the software Matlab. To complete the simulation, the user (manager or researcher) needs to collect the data and save it in the correct form. In the version presented in this work, the authors saved the data in the following format:

Table 3.2 Database for the mathematical model

	A	B	C
1	Day	Problem	Workers
2	2016-04-01	1,20	7,50

The mathematical model evaluates the quantity of problem and process improvement (workers) hours per day. In the case analysed, at the end of each day the quantity in hours of problems and process improvement were registered. The data was saved in a excel file and each line contains necessary information as detail in the table above.

The user will save the database in excel format and place it in the same folder as the Matlab code. The code is divided into six functions as explained below:

- 1- `main.m` – As the name suggests, this is the code's main file. This file makes the interaction with the user and calls all the other functions. In section 1 of the code, the function plots the graph 1 and the graph 2. The first graph displays the data available in the database as it is. The second graph also represents the data inputted by the user. But in the second graph, the author uses the Savitzky-Golay filtering (Schafer, 2011). This method is applied when the data is too noisy. It means the data varies too much with many peaks in the period. To smooth the data, the author applies the `sgolayfilt` function from Matlab.
- 2- `fminsearch.m` – In the second section of the code, the `fminsearch` calls the others function. This function applies the Nelder-Mead simplex method (Lagarias et al., 1998). This is a direct search method for multidimensional unconstrained minimization. Each time the code runs in a period, the Nelder-Mead method will verify the optimal value to use in the equation (the Function Minimum Search).
- 3- `calcul.m` – The `main.m` function calls this function `calcul.m` through the function `fminsearch`. The second section of the code calculates the parameters based on experimental data. Based on this calculation, the function plots graph number 3: "Curves with optimal parameters obtained by simulation vs. Real (+ their averages)." This graph displays the data smoothed by the `sgolayfit` function and a first simulation. Graph 3 exposes what the manager could do to have the same results but with a better employee hour distribution.
- 4- `chercher.m` – With this function, the user enters the third and last section of the code. The function `chercher.m` is also called by the `main.m` code through the `fminsearch`. The user will

determine a new objective for the problems in this function. Based on the results of the first three graphs, the user defines a new goal for her company. (In this case, the goal is always to reduce the problem level.) So, by analyzing the first three graphics, the user defines a new problem level. The author in this simulation proposes a new problem goal of 2. So the code will propose the continuous improvement hours distribution necessary to reach the goal proposed.

- 5- `equadif.m` – The `equadif.m` function works together with the `chercher.m`. In the last section of the `main.m` function, this function solves the equation using Matlab's method present in the `ode45` (Shampine & Reichelt, 1997). The function `ode45` is based on an explicit Runge-Kutta (4,5) formula, the Dormand-Prince pair (Dormand & Prince, 1980). It is a single-step solver – in computing $y(t_n)$, it needs only the solution at the immediately preceding time point, $y(t_{n-1})$
- 6- `Lotka_Volterra.m` – This function calls the variables present in the equations and links the variables, the database, and the simulation. The equations proposed in this work can be found in the `Lotka-Volterra.m` function.

Once the database is saved in the same folder of the six Matlab functions, the user will open the function "`main.m`". Before any analysis, the function will ask the number of the last line in the excel file. In this example, the authors performed the simulation with 100 lines or 100 non-consecutive days of data. The first part of the code, entirely in the `main.m` function, will provide the user the graph 1 and 2. It is a lecture on the data and distribution over time. The full code is available in the appendix A of this work. The figure below shows the six functions and their relations.

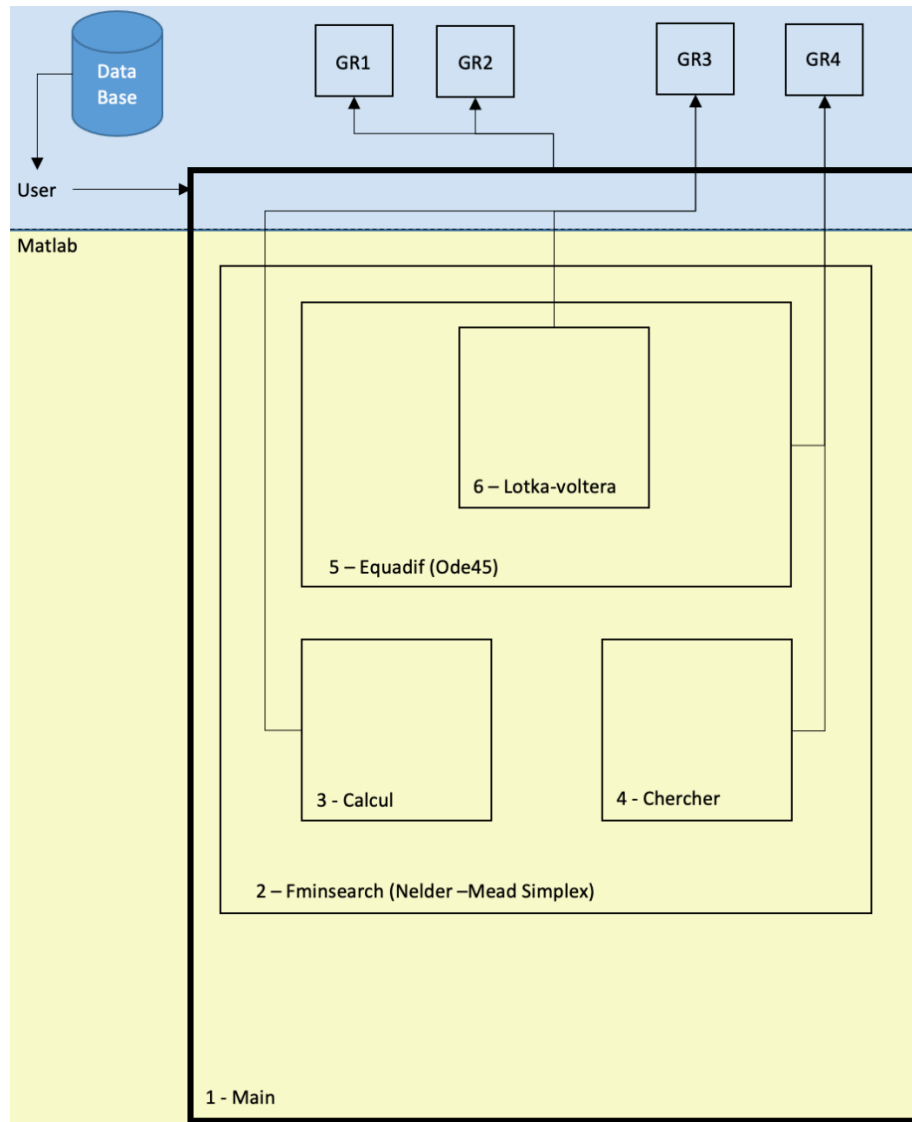


Figure 3.3 Bloc diagram of the mathematical model (Source: The author)

3.3.2 How model was tested

The author tested the method in a Canadian enterprise, more precisely, in a mechanical job-shop plant in Montreal. MITACS provided a leveraging grant to make the test operational. For confidentiality reasons, the authors do not provide the company's name, but MITACS can provide an unclassified version of the grant proposal upon request. The test occurred on 01/05/2018 and 01/09/2018. During that period, the plant had 37 employees from the shop floor, administration, and management. The employees have, on average, ten years of experience, and the company has

been operating for over 50 years. Only the shop-floor employees participated in the project, a total of 27 employees.

As preliminary settings, all the shop-floor workers were used to register their daily activities in different categories in a system. For example, employee "X" dedicated 4 hours to cut a metal part for a gearbox. So, the operator will register 4 hours in the category "A001" related to the final work for a client. This code is considered the company's objective. The employee "Y" dedicated 2 hours to organizing his work area. After that, he will register 2 hours in the category "A002" related to the improvement activity. The company used these codes for budget control.

The author of this work used these two codes to identify the two variables of the model. The variable called "Workers" is directly related to the example given by the employee "Y" and the code "A002". Furthermore, the variable called "Problem" uses the example given by the employee "X" and the code "A001". The value of this code, minus the expected time to finish a job, provides the variable called "Problem."

Once the project started, the previous six months' database was collected and analyzed to understand the initial status of the project. Based on this previous scenario, the model simulated how many hours of CI are necessary to reach the project goal. In this case, have the number of problems below 2 hours.

The project officially started with training for the shop-floor employees. This training was a general explanation of the objectives of the project. Although the employees did not have detailed information about the mathematical model and the academic research running parallel with the project, the project's author instructed the company's leaders to follow the same amount of continuous improvement hours suggested by the mathematical model.

The observation period covers 200 non-consecutive working days (100 before the CI project and 100 during the 5S project). During this test, the authors ran the model twice. One before the CI project, analyzing the scenario before the project begins and the necessary number of hours to guide the project. And a second simulation was performed after the project.

This first simulation analyzed the actual company's situation and proposed the number of hours necessary during the CI project. The table below shows those values. The simulation used the same values to find the results in the next section.

Table 3.3 Values of the variables

Variable Name	Before project	After project
Pb	2.14	2.30
W	4.4	4.73
Success rate	1.7	1.7
Communication	1.7	1.7

The values for the table above are from the database explained in the section "Mathematical code and database." These values represent the initial time in the database or the T0 of the equations. After displaying graph 1 and 2 from the data, the code will solve the equations using the methodology explained in the previous topic.

The project finished seven months later with a final review of the CI project. The following chapter discusses the results obtained during the project's implementation and the analysis comparing the real results from the project to the results from the LV model. Before presenting the results of this tool, the author will present the methodology of the other two tools in the subsequent sections.

3.4 Second tool – Using CI variables to measure Employee Engagement

As a natural sequence for the first tool, the author proposes another adaptation to the previously detailed Lotka-Volterra (LV) model. The inspiration for this work came from two papers from (Zangwill et al, 1998 and 2000). In their articles, the authors first introduce the idea of an adaption of LV to measure and forecast Employee Engagement using the data from a continuous improvement project. Previously in this work, the author introduced an adaptation of the LV model to forecast the necessary time for a continuous improvement project and consequently analyze the productivity of the CI project.

The author proposes another adaptation to measure EE based on Zangwill's idea and the first tool presented in this work. The opportunity created by the low level of EE in the companies (as presented during the introduction) and the lack of studies approaching the problem brings importance to this topic.

3.4.1 The Engagement Model

To improve the traditional EE measurement methodology, the author proposes a model inspired by the LV model. The mode is a sequel to the first model presented previously. The table below determines the relationship between agents in the proposed model and agents in the LV model.

Table 3.4 Comparison Between the Models

Proposed Model	Lotka-Volterra Model
pb = Problems =>	Sheep (prey)
w = workers (CI dedication time) =>	Wolf (predator)
e = engagement =>	Predator's food

The two equations previously proposed (Equations 2 and 3 in section 3.3), plus a third equation that will be defined further in this work, will define the mathematical model. A mathematical model is a group of equations with specific interactions between the variables where one change will impact the other.

As presented before, equation 1 in this work is the original model proposed by Volterra and adapted in different sectors after. Equations 2 and 3 are the two first adaptations used in this work. First, the derivative of the problems along the time, and secondly, the derivative of the workers along the time. The subsequent equation represents the derivative of the engagement along the time, as shown below:

$$\frac{\Delta e}{\Delta t} = -DR. \left(\frac{Pb}{w} \right) + s.c.TE$$

Equation 4 Derivative of engagement along the time (Source: The author)

The equation is balanced in two parts. The first part is the Death Rate, which will decrease naturally. The division PB per w is the result of the efficiency par workers. The more problems the workers solve, the more “energy” the system will gain. The second part of the equation is the product of the success fee (s), communication (c), and team energy (TE). Differently from the problems and workers, these data are acquired from a checklist and research.

Three variables in the model (Success fee, Communication, and Team Energy (TE)) are defined by analyzing the environment and measuring some specific points in the company. To help to find these variables, the authors of this work propose the following checklists. The researchers interested in replying to the proposed model can find closer values to their situation. The checklists are suggestions and can be adapted according to the company's situation. For example, if the company is already measuring internal communication, they can use it instead of the checklist. The fundamental point is to find a value between 0.1 and 1.

S - Success fee

The S is the coequal variable in the problem's equations (equation 2). To balance the growth rate of the problems, the variable S multiplies the average CI time realized in the period analyzed. The S estimates the leadership impact on the team's capacity for problem-solving. The next figure is the checklist to find the value of this variable.

Checklist - Success fee		
In the last six months:		
	Range	Actual level
One meeting between the supervisor and operator to discuss goals	1-25	
Empirical learning and opportunities to learn different processes	0-25	
Delegation of responsibilities	0-25	
Encourages goal achievement	0-25	
Commentaries:		
Responsibles:		
Date:		

Figure 3.4 Checklist for the Success fee (Source: The author)

The responsible for the project can interview the employees and estimate each point. Each value should be between 0 and 25 (with at least one "1" to avoid zero as the final answer). The final number should be divided by 100 to stay from 0.01 to 0.99.

C - Communication

The second equation is the derivative of the CI time. This variable is counterbalanced with variable C - Communication. The variable “C” evaluates the team's capacity to communicate efficiently, and the checklist below suggests some areas to measure communication efficiency.

Checklist - Communication		
In the last six months:		
	Range	Actual level
Internal communication measurement	1-25	
Reach	0-25	
Engagement	0-25	
Employee Advocacy	0-25	
and/or		
Employees interaction (Pentland's KPI)	1-100	
Responsibles: _____ _____		
Date: _____		

Figure 3.5 Checklist for Communication (Source: The author)

The variable C comprises 4 points or one global indicator called Pentland's KPI. The responsible for the project interviews the employees and measures their impressions about the communication potential of the company. The four points to consider when talking about the communication potential are:

- 1 - Internal communication measurement
- 2 - Reach
- 3 - Engagement

4 - Employee advocacy

Pentland's KPI (Pentland, 2012) can substitute these four points.

TE - Team Energy

As addressed before, the third variable is called Team energy. And it is the counterpart responsible for balancing the engagement's natural reduction (death rate).

Checklist - Team Energy		
In the last six months:		
	Range	Actual level
Opportunities between work/life	1-20	
Rewards and Recognition	0-20	
Career Opportunities	0-20	
Enabling Infrastructure	0-20	
Learning and Development	0-20	
Commentaries:		
Responsibles:		
Date:		

Figure 3.6 Checklist for the Team Energy (Source: The author)

This checklist has 5 points. These points should be investigated by the project responsible with the company's employees.

1 - Opportunities between work/life

2 - Rewards and Recognition

3 - Career Opportunities

4 - Enabling Infrastructure

5 - Learning and Development

The range is the same as the two previous variables, but with a max of 20 points.

To better understand the model equilibrium, the author proposes a causal loop diagram. The figure below shows the model causal loop and defines the interactions between the variables.

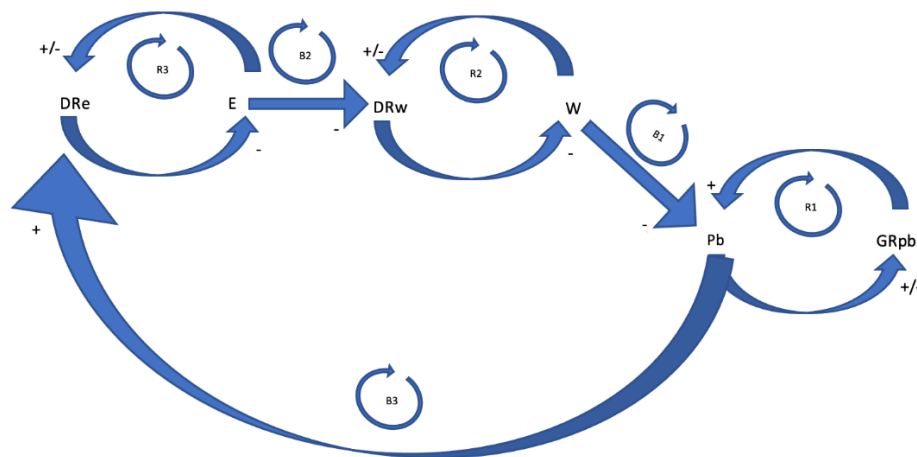


Figure 3.7 The model causal loop (Source: The author)

The meanings are the same for both pictures, unless for the following variables:

Dre = Engagement death rate;

E = Employee engagement;

DRw = Worker's death rate, and;

GRpb = Problems growth rate.

The main difference between the first causal loop presented in section 3.3 and the causal loop just presented is the addition of the Employee engagement variable. As the picture demonstrates, increasing the problems can increase the engagement death rate. The *increase* in the death rate will *decrease* employee engagement.

As enunciated previously, this relation is only found in the Lotka-Volterra model, which is why the author chose to use this model as inspiration.

This equation compares the "energy" necessary for the predator to hunt the prey. This energy is the engagement, and the preys are the company's problems. The employees perform CI actions to reduce the number of these problems. The engagement could also be considered as the fuel to keep the CI actions present; The workers perform more improvement activities; more engagement is developed to keep doing the circle. On the other hand, when the workers complete fewer actions, the engagement reduces, and the circle spins naturally down.

To better understand the variables presented, the table below defines each of the variables. (Equations 2, 3, and 4 in this work)

Table 3.5 Employee Engagement and CI variables

Variables	How to calculate it
GR	The behavior of Problems amount (Naturally increasing)
S	Consider the result of the Checklist - Success Fee
w	The average employee CI time
DR	The behavior of Workers amount (Naturally decreasing)
C	Consider the result of the Checklist - Communication
Pb	Problems average
DRe	The behavior of CI actions amounts (Naturally decreasing)
E	Consider the result of the Checklist - Team Energy

3.4.2 Proposed methodology to test the model

The methodology to test the proposed model is similar to the methodology applied to the previous tool of this work. This method consists of (1) observing the actual comportment in the process, (2) formulating hypotheses (3) testing the hypotheses through experiments. The results will be (4) analyzed to support an empirical conclusion. This work introduces a model able to perform a "dynamic visualization of the engagement." It has the word "dynamic" because, differently from the classic methods available in the market, this article proposes to visualize the team engagement along with a CI project, and not a punctual measurement through a survey as the classical method. The authors divided the methodology into six sub-parts:

- Adapt the LV model to include the Team engagement equation;
- Measure the initial level of EE with a classical method;
- Implement a CI project;
- Analyze the data from the project with the equations proposed in this work;
- Measure the final level of EE with the classical method;
- Compare the results from the classical method with the data collected during the CI project.

The CI project, cited in the third item above, allows employees to improve their processes. Also, it provides ideas for further improvements and data to measure engagement. Several authors linked the CI methodology with the EE (Charron-Latour, 2017; Coleman, 2004). For these authors, the company's transformation occurs on the shop floor. Based on this affirmation, this work aims to provide a similar empowered environment and measure engagement with the method proposed here, analyzing three possible scenarios:

- The Continuous Improvement project increases engagement.
- The CI project decreases engagement.
- The CI project and engagement are not related (That is, the association is spurious).

A comparison with the classical method (the EE surveys provided by different organizations) is fundamental to this methodology. It acts as a calibrator to ensure the accuracy of the proposed mathematical model. Once both methods have similar results, it is possible to conclude the mathematical model's accuracy in this work. Nonetheless, the author could not test this

methodology as made for the first model due to external forces. For this reason, the model main result is the (1) discussion about the problem's importance and the (2) model proposition. These results and a later conclusion are presented in the next paragraphs (Instead of the chapter results, where is presented the analytical results of the first and third tools).

3.4.3 Expected results from this model and first discussion

The model with three equations and the methodology are the main results of this tool. Implementing the classic method (Gallup Q12 or any available methodology to measure EE) is fundamental for testing this tool. After implementing the first model, the author searched for new opportunities to test the second model and implement the complete methodology preset in section 3.4.3. Unfortunately, the author did not find an appropriate company to test the second tool during the length of this work. Without the real data, the author was unable to calibrate the model.

Even without actual engagement data, the author used the former project's data to test the equation with a numerical solution. The result of this theoretical test was:

- 1 - The results leaned to the chaos. The numerical solution is extraordinarily sensible, and a change in thousandths (0,00X) in the input can completely change the output.
- 2 - The variables to measure engagement should be validated and compared with the classic models. The author proposes three variables to balance the equations: Communication, Success fee, and Team Energy. These variables are found in the literature review of a continuous improvement project and the classic models, but the methodology to gather this data in the company should be tested.
- 3 - Although employee engagement is the problem presented in this work with the most representative financial impact, the definition of engagement between the classic models and the definition of engagement linked to the CIP are not the same. This can cause the relationship between the gain of employee engagement and financial gain to be dubious.

The author suggests performing more tests, gathering more data, and trying different solutions for the model. Statistical solutions (i.e., machine learning) can convert data into categories. These categories can englobe the categories of employee engagement and avoid the chaotic result.

The classical method is an essential base for measuring some specific engagement points. Nevertheless, the results are temporary and could be influenced by some bias. When the variables between the methods (CI and EE) are compared, it is possible to identify the relation between them. Based on this correlation, the work presents a method to compare the two methods and propose a simulation for the future.

This work introduces a mathematical model to understand the relationship between eight variables present in the companies (and fundamental for any continuous improvement project) and its relationship with Employee Engagement.

The work also presents a methodology to measure employee engagement and analyze the impact of the continuous improvement project on engagement. The methodology should be tested in different environments and analyzed with a different statistical model to find the possible correlation between the CI project and the EE.

3.5 Third tool: Simulating the impact of participatory management

This section will provide the methodology for the third tool presented in this work. As shown in the introduction and section 2.6, this model aims to predict the impact of participatory management in different scenarios of a continuous improvement project.

The author proposes this model due to the relationship between productivity, the first model, and participatory management. According to (Weber, 2005), 88.9% of managers believe in increased productivity after implementing participatory management. Another link between the models is the learning curve (LC). LC is a company's capacity for improvement based on the employee's knowledge. Zangwill and Kantor (Zangwill, 1998) said that the LC provides a means to track continuous improvement actions. However, no research has tried to measure or simulate the PM based on LC model. This work aims to provide a model to assess this impact in a process improvement change.

This proposal uses the multi-agent system (MAS) because of the benefits of interaction and communication among agents. MAS is also an alternative to the systems of equations used in the first two models. Using the appropriate algorithms, the agents can make decisions and learn from their interactions. The model is inspired and based on the Ordinary Differential Equations proposed

for model 1 and 2. To simulate the model, the author uses the software Netlogo. An open-source software made by Northwestern University.

The multi-agent model was developed through a literature review and discussion with the CIMAR-Lab research group. To calibrate the model, the author used the software Netlogo and analyzed the agent's comportment. The results of Zangwill et Kantor (Zangwill, 1998) and the Lotka-Volterra model are a natural inspiration for this model.

Some questions are pondered with this methodology:

- How to validate the model efficiently against real-world data?
- How to calibrate the initial values to consider different companies and sectors?
- How to build a simulator based on real-world data using, for example, internet-of-things?

These questions are discussed in the results chapter.

The first practical implication of this model is creating a method to help the managers and consultants in continuous improvement to understand their company better and adapt the best management style for their situation faster. This method aims to achieve higher participatory management in the organization and implement a continuous improvement culture surrounding the employees.

Based on the literature review performed during the second chapter, this work aims to test the hypothesis that the multi-agent system can accomplish a simulation of Participatory Management in a continuous improvement change.

The methodology to test this hypothesis is based on four parts:

- Review the literature to construct a model of participatory management;
- Define a set of differential equations to guide the performance of the model (These equations are mainly focused on the first and second models presented in this work);
- Build a multi-agent system simulator;
- Run the simulator with real data.

This methodology aims to answer some questions, such as:

What is the importance of engagement in Participatory Management?

How is it possible to simulate participatory management?

These questions link the second tool and the third tool. The chapter results and discussion will revisit these links.

3.5.1 Model features

As informed before, to perform the simulation, the author used the software Netlogo. The figures below show the interface of the software. The software interface is divided into three main parts. The "interface" is where it is possible to visualize the environment (or world/scenarios) and the command control, with buttons, sliders, and other controls. And the indicators. The second tab in Netlogo is called "Info," where it is possible to describe the program. The third tab is called "Code," where all the code for the simulation is written. The full code is available in appendix B of this work.

The figure below shows the command control of the simulation. It is possible to choose different parameters in the red boxes A, B, and C before starting the simulation. Pressing the button "setup," all the commands are prepared. When pressing go, the simulation starts. All figures from here until the end of the work were made by the author.

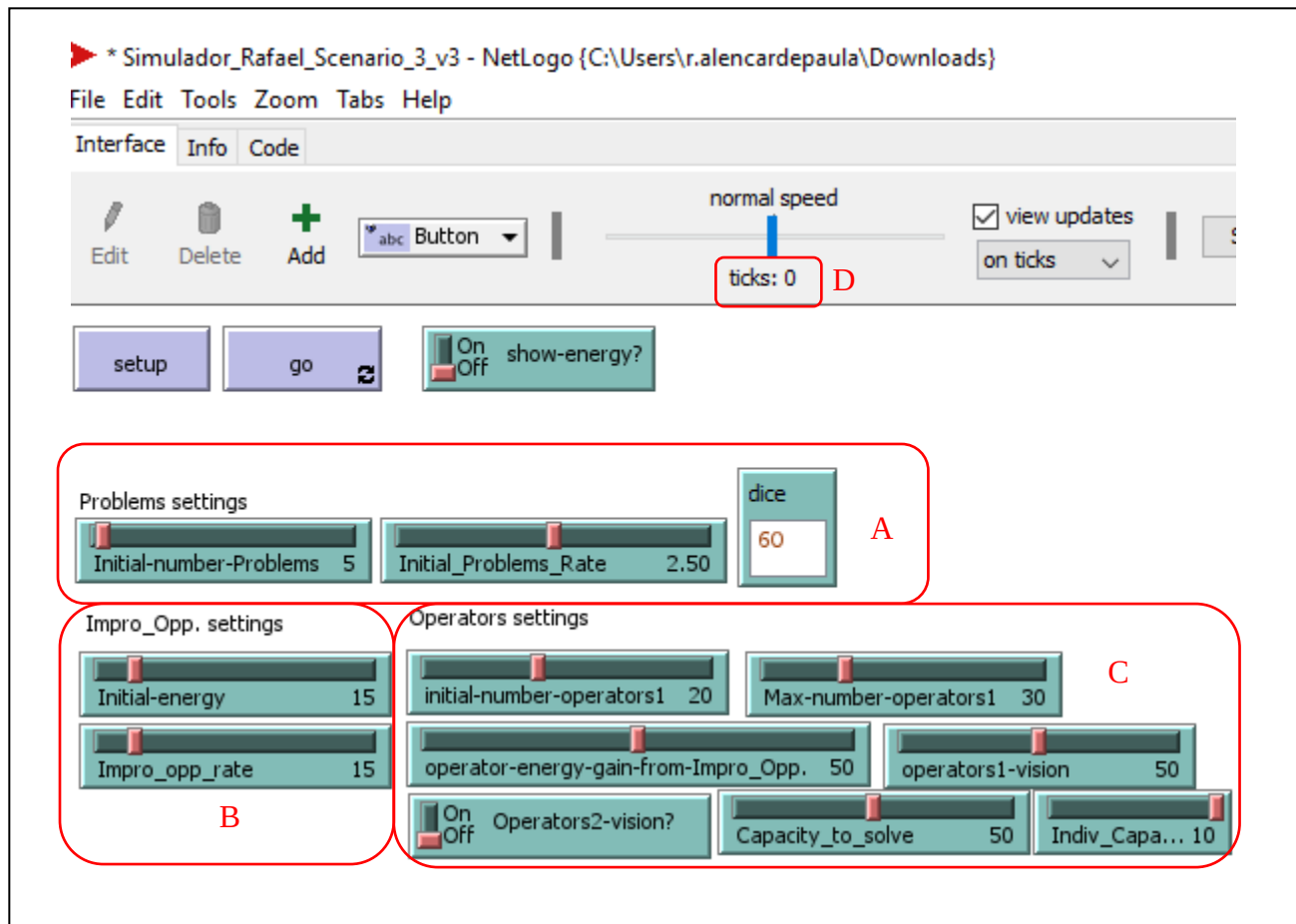


Figure 3.8 Netlogo Interface – Commands details

Problems, Problems Growth rate, and Dice

The variable called "Problems" in this model follows the same function and description of the previous models. As defined in section 3.3, a problem is a waste hour. If the client pays 5 hours to the company to finish a job, and the company takes 7 hours, the difference (if positive) is what the author defined as a problem.

For the simulation, where possible, the author used the data from the project of the first model. The new variables start with a hypothetical initial number and "reproduce" at a hypothetical rate. It is also hypothetical the rate by a probability called "Dice." If, during a specific tick, the probability creates a new failure, the system will create according to "Initial_Problems_Rate." The figure above, point A, highlights these controls.

Improvement Opportunities

The total of improvement opportunities available is a percentage of the total of problems. The work determines this percentage with the slider highlighted below: "Impro_opp_rate" Figure above, highlight B. Differently of the problems, the "Improvement_opportunities" has the feature "Initial-energy." This variable represents the lifetime of the opportunity. For each tick, the energy is reduced at one point. When it reaches zero, the opportunity disappears.

Workers

The model proposed has two types of Workers. Although Worker 1 searches for improvement opportunities with the feature "vision", worker 2 does not have this feature. In this case, worker 2 is limited to solving the opportunities only if he passes through them. Both workers follow a random path, but when an improvement opportunity enters the "vision field" of worker 1, he changes their way forward to the improvement opportunity. The slider "Workers1-vision" determines the size of his vision. The figure below gives a reference to this vision.



Figure 3.9 Worker Vision

The vision is the capacity of the Worker to see a problem. So, the bigger the Worker's vision, the bigger the capacity to find problems. When the Worker finds an improvement opportunity, he has a probability of solving it. The probability is defined by the "Capacity_to_solve" number.

The number of Workers starts with an "initial-number-Worker," and it is limited to a "Max-number-Worker1". This range is the number of available employees in a department or company. Similar to the improvement opportunity, the Workers have "Energy" and waste energy at the time.

When the energy reaches zero, they die. Differently from improvement Opportunities, the Workers can receive more energy in their process. When they find an improvement opportunity, they receive a quantity of Energy. Defined by "Worker-engagement-gain-from-Impro_Opp."

Worker 2 has the same features as Worker 1 (engagement, initial number, die). The difference between them is *the vision*. Worker 2 walks randomly; when he crosses an improvement opportunity on their way, the capacity_to_solve probability runs. Figure above, highlight C, defines the commands related to the Worker.

Worker's reproduction: The system will evaluate if it is necessary to call/hire/create another Worker or not. This reproduction system is based on their capacity ("Indiv_Capacity") to solve an improvement opportunity. It is essential to say that the individual capacity differs from the capacity to solve. In contrast, the capacity to solve represents the intelligence of the Worker (higher number, easier to solve). The individual capacity is related to how many opportunities the Worker could work on daily.

During the simulation, Netlogo counts the time. The time in Netlogo is measured in "Ticks," as highlighted in the red box D in Figure above. In every simulation, the number of ticks starts at zero. In this work, the ticks start at zero and continue until the user stops. In the figure below, it is possible to see the two different scenarios. The upper part in green is scenario one, where the agent actively looks for an improvement opportunity. On the lower part, in blue, the agent does not change its direction to find an improvement opportunity. The agent does his same daily work, and if an improvement opportunity shows up his way, the agent will try to solve it. The initial number of agents is the same in both scenarios, and a line marks the aleatory way that the agent follows.

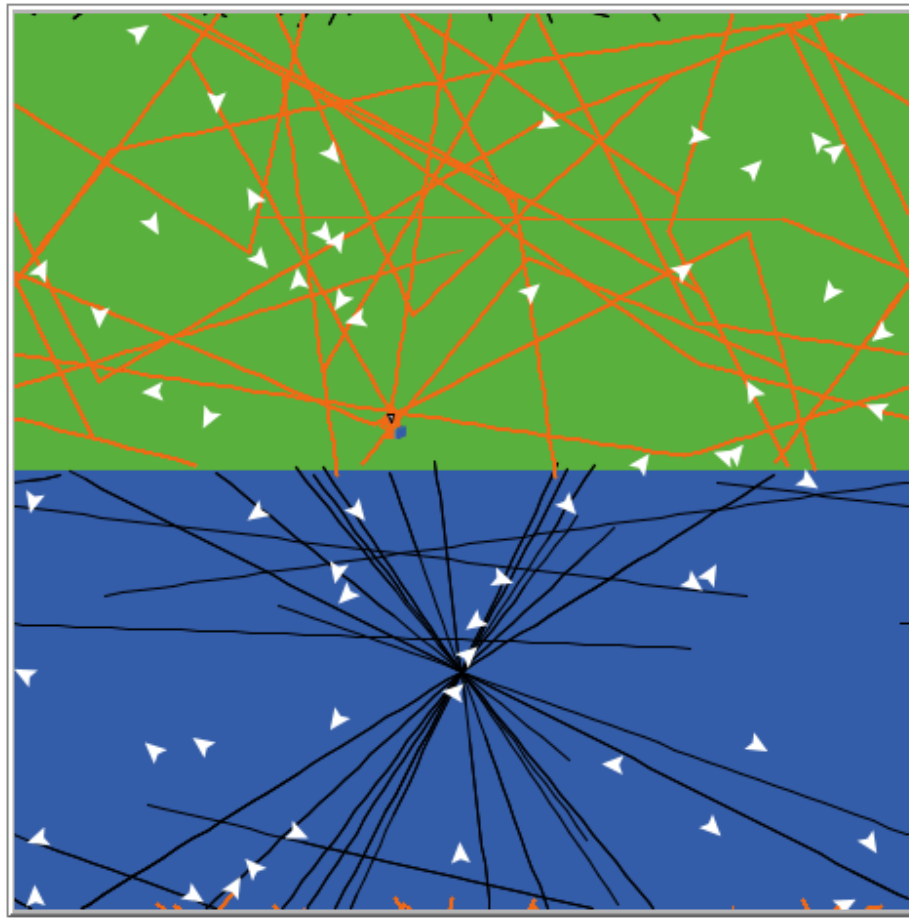


Figure 3.10 Visual Indicator between the two scenarios

The figure below details the indicators referent to the agents in scenarios one and two. The population's graph is the primary indicator in this simulation. The graph on the right side shows the total number of problems solved, the number of improvement opportunities, and the number of operators 1 and 2. And the text boxes beneath the population's graph show the actual number of each population. The graph on the right side sums the total of problems solved.

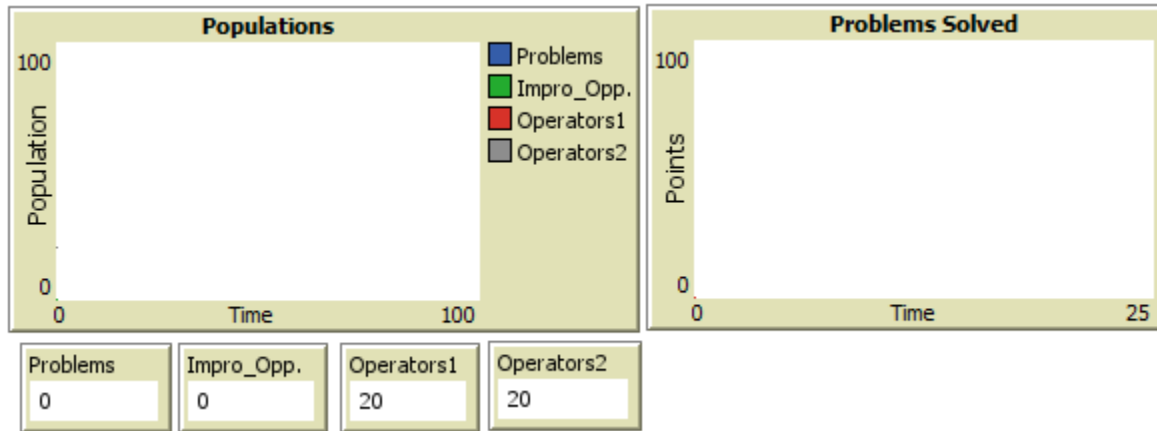


Figure 3.11 Populations Balance and Problems solved Indicators

3.6 Conclusion

This chapter presented the methodology for the three main parts of this work. The first proposition provides a methodology to implement the “productivity” model. This first tool introduced the idea of the link between Lotka-Volterra and continuous improvement. This methodology was tested in a company in Montreal. The first improvement for this model is presented in the second part of this chapter. The author proposes a third equation to balance the problems, the CI time, and the engagement. And after that, the author presents the third methodology. The link between LV and CI is still applied, but the author uses another tool to explore the model in this methodology. This tool is the multi-agent system simulation. The next chapter shows the results of the models and prepares the discussion and conclusion in the last part of this work.

CHAPTER 4 RESULTS

The reader will find in this chapter the results of each model. The results are presented as the models were implemented. The first model presents the data analysis before the model was implemented and during the continuous improvement project. The second model is a proposition, and as explained further in the thesis, the model will be tested in the future. For this reason, this chapter does not present the results for the second model. The third model results are discussed in this chapter. The author discusses some of the scenarios proposed. For the other scenarios, the reader can address appendix C.

4.1 First tool - Lotka-Volterra model adaptation for productivity model

Managing limited capacity for improvement within manufacturing systems is a goal sought by every industrialist to achieve excellence. Several works have investigated potential algorithms to adequately allocate the role of control to achieve higher process quality: The work of Bettayeb, Bassetto, Vialletelle and Tollenaere (2012) introduces a heuristic algorithm to allocate quality control capacity to minimize the risk of producing non-conformities. They applied it in the semiconductor industry, generating millions of dollars in gains due to reduced risk of scrap parts and significant recalls.

Those works focused on inspection capacity and allocation depending on the product default level. However, the author of this work aims to complete the literature where no, or just a few, attempts exist towards *the human aspects*. The investigation of Fiegenwald, Bassetto and Tollenaere (2014) is an introduction of a new concept to help quality improvement teams prioritize their actions on detecting performance barriers. To the author, this is the first attempt to reanalyze a CI project directly based on *the teams* and not only automate or control devices.

Unlike previous works, this current work introduces a tool that can link "*the continuous improvement team design*" (number of participation hours for the team) with the *number of problems solved*. As explained in the previous chapter, the methodology of this work proposes an emulation tool based on and adapted from the Lotka-Volterra (LV) model.

The work divides the results into three sections. The first explains the results found by the model using the database before the 5S project starts. The second section is the analysis of the period during the formal 5S project, and the third section is a conclusion of the results and discussion.

4.1.1 Analyze Before the Project

The figure below, "Workers and Problems Total - Before the Project," presents two measurement and their averages. The top dotted line (Wk Real) is the time dedicated to every training or development in the process or personal space. The red line is the average. The second dashed line (Prob Real) is the variable problem, as explained in the section 3.3, with his average in grey.

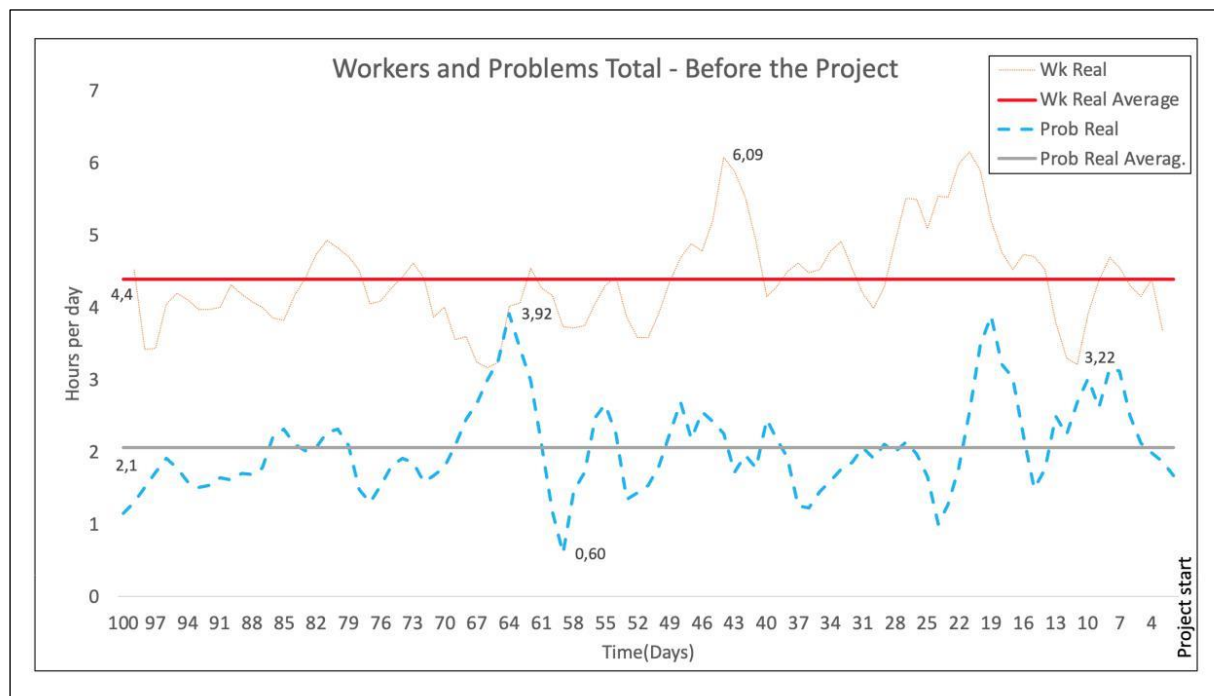


Figure 4.1 Workers and Problems Total - Before the Project

This figure shows the time dedicated to continuous improvement before the 5S project starts. Even before the project, the employees had the opportunity to improve their work in a *decentralized and individual* way. The company did not follow the number of problems, but it was available, registered, and compiled in its database. As observed in the "Wk Real" curve, the dotted line reaches a peak of 6.09 hours just 45 days before the project starts. The average time devoted to CI during those 100 days is 4.4 hours; this is the variable Wk - Before the Project.

Before the test began, it was observed in the "Prob Real" a peak in the number of problems. The peak was just 64 days before the 5S project, with a value of 3.92 hours.

According to the analyses realized during this period, the peak of problems is not linked with the peak of CI actions (represented by the Wk Real line). Even if actions were defined as "*firefight mode after the problem arrives*," there is no analyzed association between the number of problems and the CI actions. The actions were individual, and there was no follow-up in the problem variance.

It is also noticeable in the lower straight-line (Prob Real Average.) that the average time spent daily on problems is 2.1 hours per day, ranging between [0.6; 3.92]. This number is lower than the average amount of improvement and training, of 4.4 hours per day, observed in the top straight-line called "Wk Real Average". CI time ranges between [3.22; 6.09].

The Figure below, "Correlation between Prob Real and Wk Sim - Before the Project," is the first analysis provided by the model. It compares the number of problems hours before the project, in the dashed line called "Prob Real," with the number continuous improvement time that the workers should do in the project's second phase. It means the organized 5S CI project led by the author of this work. This number is represented by the dotted line called "Wk Sim."

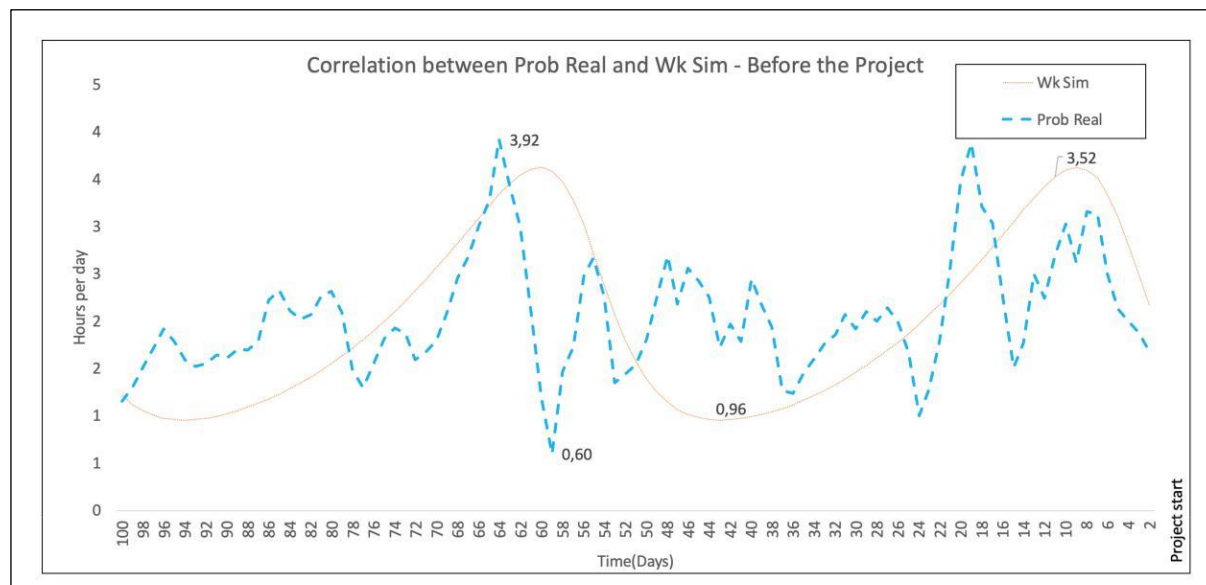


Figure 4.2 Correlation between Prob Real and Wk Sim - Before the Project

Figure 20, according to the dotted line - WK Sim, the model distributes the number of improvement hours in two waves. The first wave starts after the peak of the problems, around 60 days before the project start. And with a maximum continuous improvement time of 3.58 hours on that specific

day. The dotted line gradually increases the number of improvement hours and suggests to the workers to perform just 20 days in this period with more than 2 hours of continuous improvement dedication. Following this strategy, the number of problems reaches a peak of 17.43 hours in one day. (As it is possible to see in the dashed line - "Pb Sim" in the figure below.

The model's new distribution proposes concentrating on the CI employee's time after a planning period. It is considered a planning period when employees do less than two CI hours daily. During this period, the employees also perform daily small improvement actions. The managers did not implement these daily discussions and follow-ups in the period before the organized project.

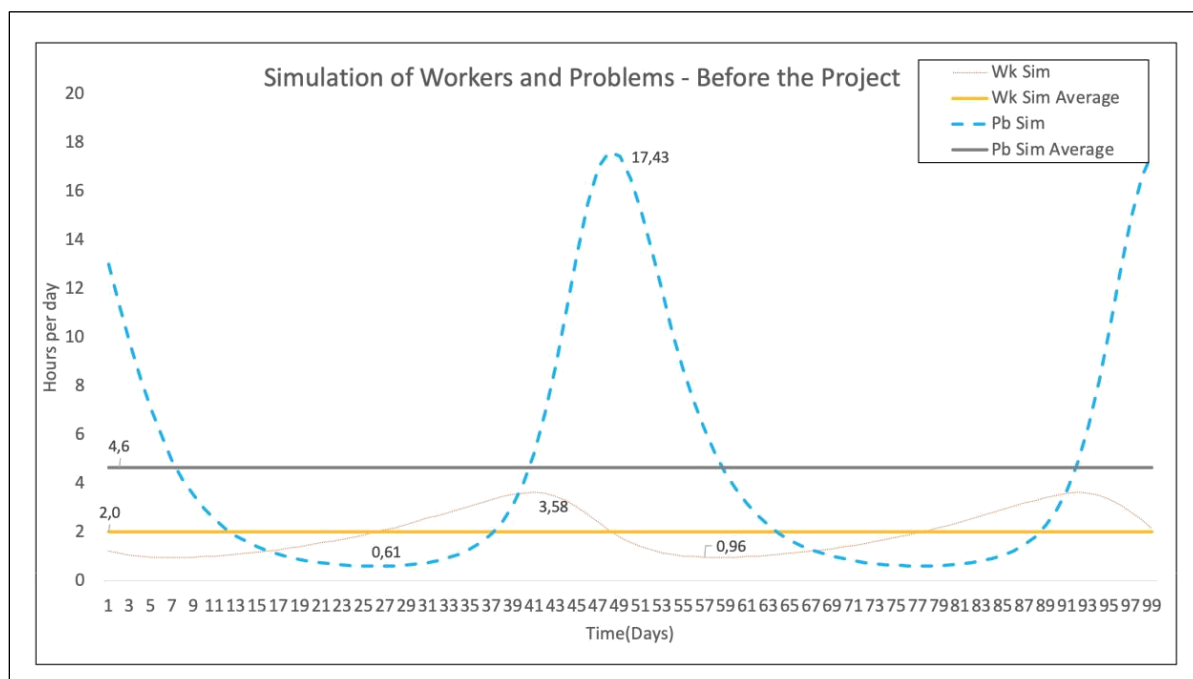


Figure 4.3 Simulation of Workers and Problems - Before the Project

Figure 21 shows how many CI hours the workers should do during the organized CI project. Based on this simulation, the company's management was oriented to perform a CI project. Once the management follows the simulation, the CI time will follow an average of 2 hours per day with two peaks of 3.58 hours each. Theoretically, the number of problems would follow the dashed line with an average of 4.6 hours per day and one peak of 17.43 hours on day 50. The model redistributes the two "populations" of the system according to the Lotka-Volterra model. Based on it, the model reduces the number of hours to improve the process by 53%. This 53% represents the total number of improvement hours of 425 (done previously by the workers) to 199. This redistribution avoids the peaks observed in Figure 20.

On the other hand, this strategy also increases the total number of problems by 125%. The number of problems in the period before the project was 204 hours. After analyzing and redistributing the hours based on the improvement hours forecast, the model simulated 459 problem hours. The model distributes the number of problems in the period, and instead of several ups and downs, the model simulates just one peak, as observed in Figure 21.

4.1.2 Analyze During the Project

The analysis during the project analyses a hundred days during seven months (in the same way as the "before the project", only the days with data are considered). Thus, it is possible to compare the two periods: "before the project" and "during the project." The project's starting point is the first general meeting with the shop-floor workers in the company. The author explained the global view of the project and its objectives.

Figure 22, "Workers and Problems Total - During the Project" displays the behavior of the CI time (in the dotted line called Wk Real and its respective average) and the overtime (in the dashed line called Prob Real and its respective average) during the project.

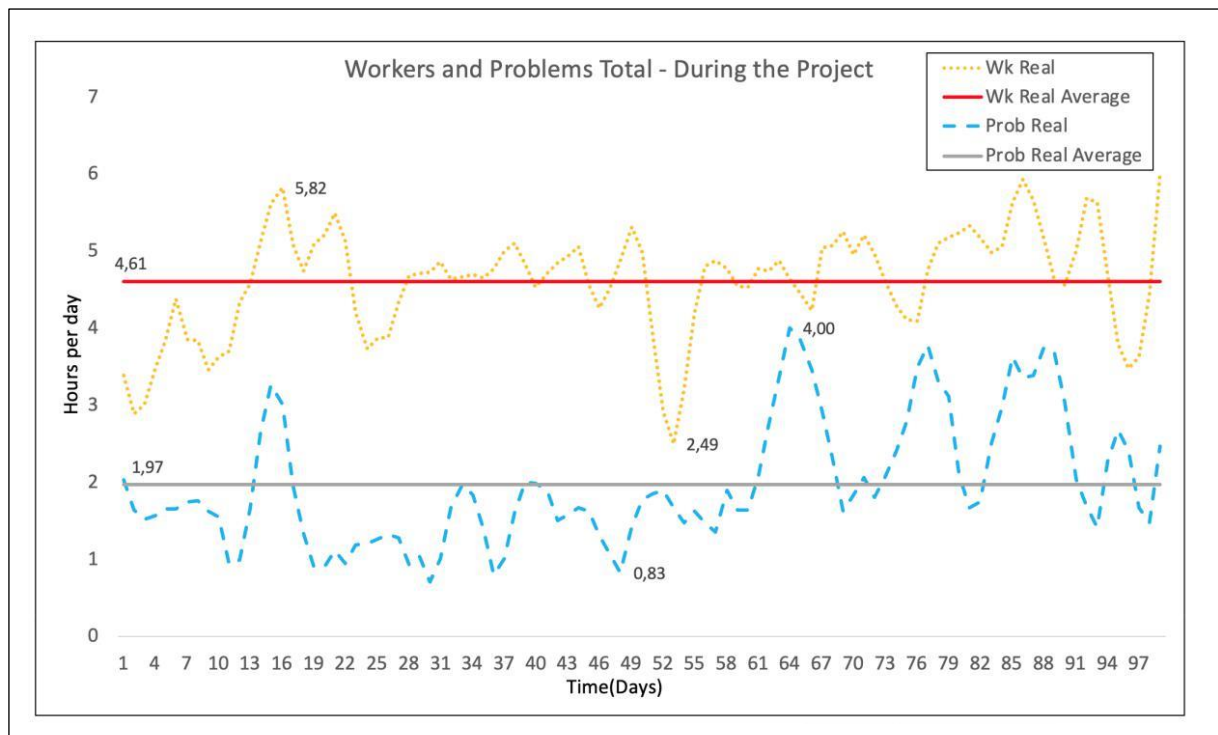


Figure 4.4 Workers and Problems Total - During the Project

One essential point from Figure 22 is the higher amount of CI time observed in the straight-line called "Wk Real Average." During the project, it was 4.61 hours per day. It is, on average, around 20 minutes more per day than the previous period. It is not just more time but also focused work with an organized methodology to reduce the number of problems in the company. As observed in the lower straight-line called "Prob Real Average," The number of problems was just below the Goal of 2 hours per day. With an average of 1.97 hours per day.

Figure 22 shows the continuous improvement hours performed during the project in the top dotted line called "Wk Real" and the simulation provided before the start of the project in the lower dashed line called "Wk Sim". To test the model, the author proposed that the company's leaders implement a continuous improvement project and plan the dedication time of the shop-floor workers according to this dashed line. This approach is the base to determine if the adapted Lotka Volterra model can predict the CI project.

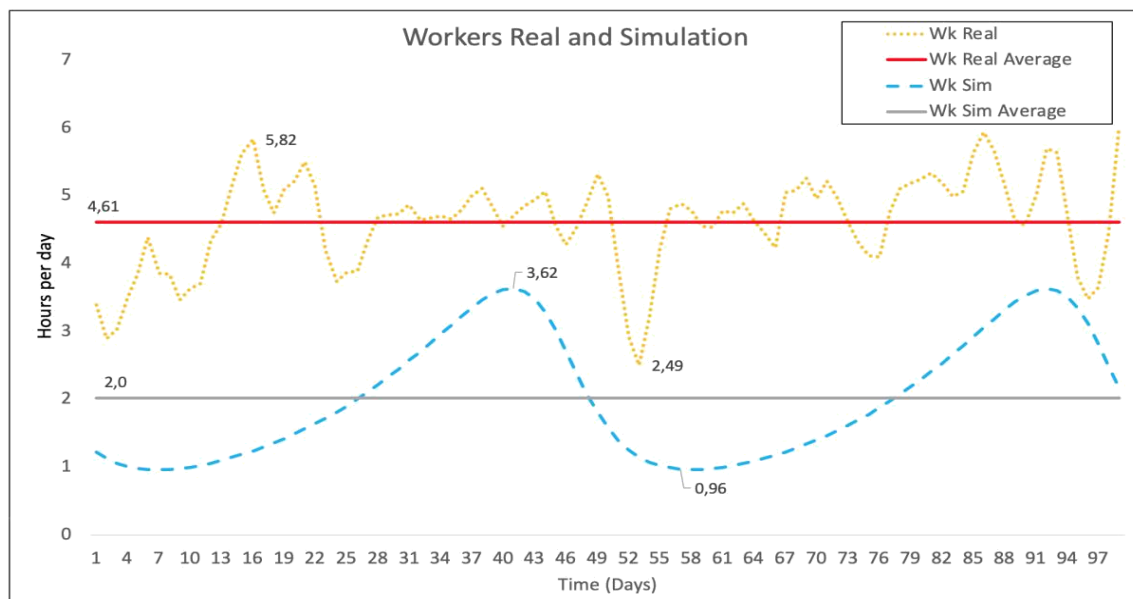


Figure 4.5 Workers Real and Simulation

As observed in the lower straight-line called "Wk Sim Average", the model proposes an average of 2 hours per day. The shop-floor workers should plan their work in two waves of continuous improvement of 3.62 hours, as observed in the dashed line "Wk Sim". The first peak, with 3.62 hours in one day, is on day 40, and the second is on day 91. As the graphic shows 100 days of analysis, it is possible to see the two first continuous improvement waves.

Furthermore, in Figure 23, it is possible to see the difference between the real-time performed by the shop-floor workers in the top dotted line and the simulation in the lower dashed line. The real continuous improvement hours doubled the simulation made by the model. Only around days 53 and 97, the continuous improvement real hours are under the peak hours simulated by the model.

In this graph, it is possible to observe the model distribution of the problems in two peaks, one around every 50 days. Due to the analysis being made in 100 days, the first peak is evident in the middle of the period analyzed, and the second starts around day 90. Each peak estimated by the model has around 25 days with problems more significant than 2 hours, and the highest number in the scenario estimated by the model is 17.63 around day 49. Although it is impossible to see the second peak in the same graph, the behavior in the second part of the graph is the same as in the first part. In this graph, it is also possible to observe the difference between the two behaviors. The adapted model estimated a simple behavior, considering the problems according to the workers' behavior. However, as discussed before, company reality has a complex behavior, not just based on the employees' CI dedication time. When the reader verifies the average of the two behaviors, the two straight lines in Figure 23, the actual number of problems is only 42% of the number estimated by the model. The lower straight-line, called "Prob Real Average," has 1.97 hours of problems, and the top straight line, called "Pb Sim Average," has 4.64 hours of problems during the same period. Although the difference between the real and the simulated, this difference shows the alignment with the model. Because the workers made more than 2.3 times the continuous improvement hours, the problems were 42% of the model's expectations. The two averages show the impact of the continuous improvement project. Because the project leaders performed more hours than the amount estimated by the model, the number of problems was also below the estimated by the model.

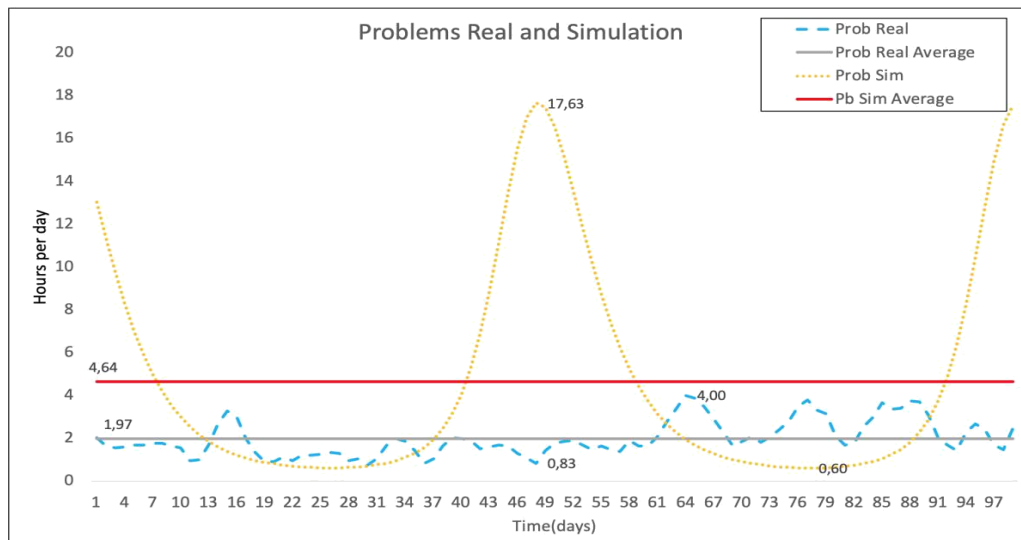


Figure 4.6 Problems Real and Simulation

As explained previously, this behavior is caused by a model unable to understand the nature of the problems in an industrial process. Although it is possible to control the number of CI hours and distribute them logically to follow the model, it is impossible to expect the same from the number of problems. The real number of problems did not show any of the peaks estimated by the model, but it followed a natural path in the development of the problem see the dashed line called "Prob Real" in Figure 24. On average, the number of problems was 0.3 below the goal of 2 hours per day. Although this average, the dashed-line "Prob Real" had a growth in the number of hours of the problems starting after day 60. It is not directly linked, but around day 53, the process found the lowest day in hours of continuous improvement, as observed in the dotted line called "Wk Real" in Figure 23. A few days after the CI hours decay, the number of problems was consistently 95% over the average and 90% under the average before the decay. The number of problems was reduced until this decrease in CI. This second part of the project placed the number of problems incrementally again.

One impact of this difference can be analyzed in Figure 25, called "Relation Real and Simulation". In this graph, there are two lines and their respective averages. The dotted line represents the relation between the Worker's Simulation and the real. Furthermore, the dashed line presents the relation between the Problems real and simulated. On average, the relation between the Worker's Real and simulation was 228%. It means that the shop-floor workers performed more than double the hours indicated by the simulation. Following the two valleys of the dotted line called "Wk Real

Dur/WK Sim Bef," the reader can find the two depressions, one around day 41 and another around day 97. During these two lowers periods, the shop-floor workers yet performed 130% of the hours proposed by the model. In the two peaks of the dotted line, the workers realized five times the necessary number of hours proposed by the model. The biggest one, around day 57, the model proposed less than one hour per day, 0.96, and the workers performed almost 5 hours of continuous improvement.

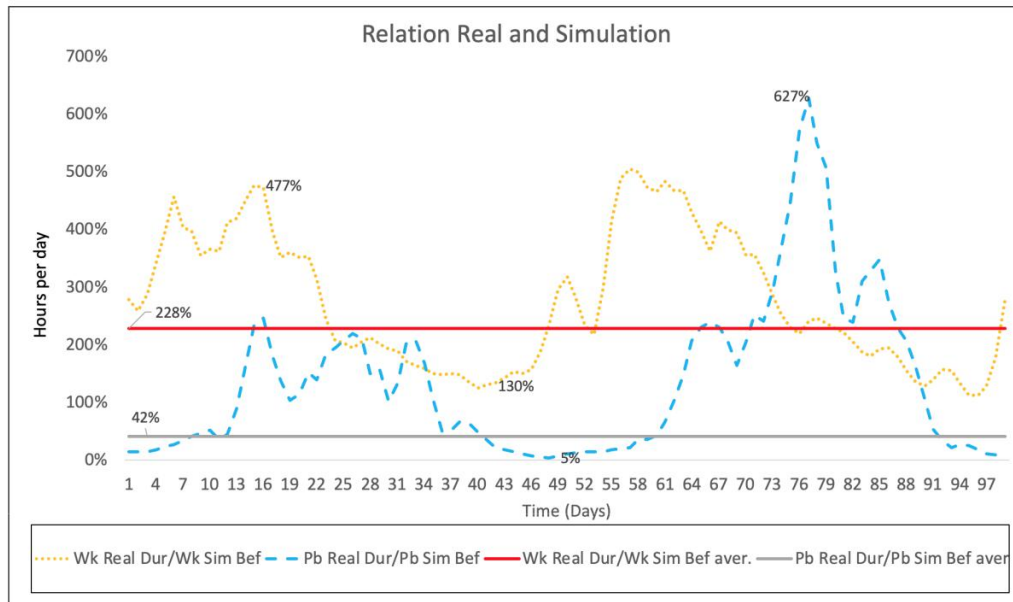


Figure 4.7 Relation Real and Simulation

Moreover, it is possible to see similar behavior at the first peak of Figure 23. Around day 15, the workers performed 5.82 hours of continuous improvement, and the model proposed a planning period with around one hour of continuous improvement. These hours could be used, for example, to plan or verify the process. To perform short discussions and round tables about the indicators and standard work.

In the same graph, the reader can observe the relation between the numbers of real problems over the simulation in the dashed line called "Prob Real Dur/Pb Sim Bef". It is possible to see the two periods where the simulation was under one hour (between days 10 and 35 and days 61 to 91) and the period of the peak in the simulation, where the real problems were under one hour and the simulation estimated 17.63 hours of problems in one day. On average, the relation was 42%. It means that the model's number of real problems was less than half-expected.

It is possible to see the similarities when analyzing the two relations together, as done in Figure 12. The shop-floor workers more than doubled the continuous improvement hours suggested by the model. Consequently, the number of real problems was lower than the half estimated by the same simulation.

Estimating the necessary time for a continuous improvement project is not the standard process in the market. The time dedicated to a CI project is defined by the time available in the company and the standard methodology available in the literature. Due to this, the project leaders who implemented the project expressed the difficulty of following the model's forecast.

The last graph in the discussion, Figure 26, shows the last simulation performed by the same model. This new simulation was performed at the end of the project and is a forecast for the next project. This new simulation was not tested in the company due to the project's discontinuation. However, it is possible to see the behavior shaped like the Lotka-Volterra model implemented in waves.

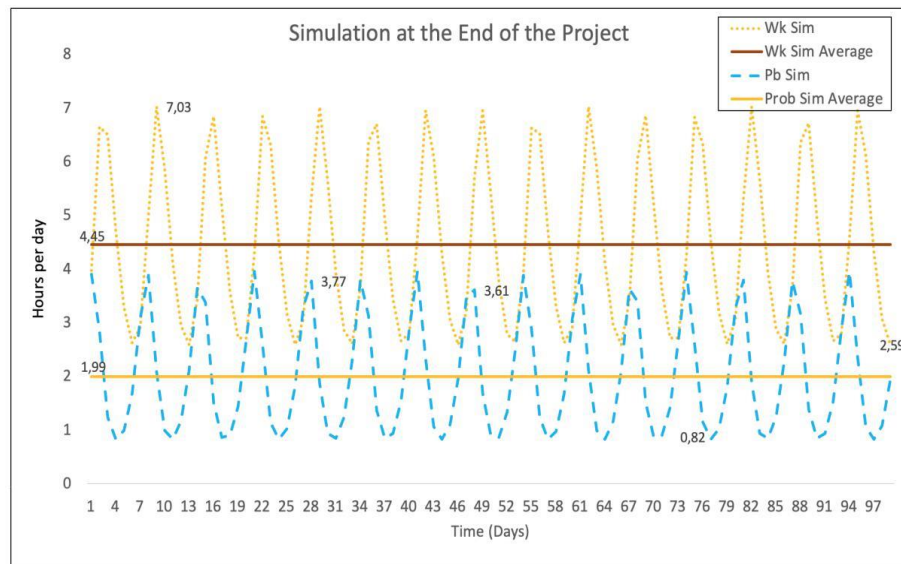


Figure 4.8 Simulation at the End of the Project

The new forecast estimates an average of 4.45 hours per day of continuous improvement hours and estimates 1.99 hours of problems. The wave shape of implementation agrees with the current LV model. The project leaders follow a methodology where they can analyze data and perform follow-ups, followed by days where the employees can dedicate more time to implement continuous improvement actions.

This last simulation reduces the number of continuous improvement hours and organizes them in a usual manner. It also keeps the problems lower the goal of 2 hours per day.

4.1.3 Conclusion

This work introduces a mathematical model to understand the relationship between the time wasted in overtime and the process improvement time. It proposes to analyze the data and simulate the CI necessary time to reduce the number of problems.

Nowadays, managers will define the necessary time for CIP based on the employees' availability or the problem's urgency. Although the importance of the Lotka-Volterra model and the introduction of the work of (Zangwill & Kantor, 1998) and (Zangwill & Kantor, 2000), adapting the LV model to the learning curve, the author did not find a similar tool to forecast the number of problems using the Lotka-Volterra model.

As a result, the author: (1) Developed a mathematical model to estimate the employee human resources dedication versus the impact on the number of problem hours. (2) Implemented a 5S project to test the model, and finally (3) analyzed the data to find the relation between the schedule suggested by the model versus the schedule followed by the employees.

The model suggested an average of 2 hours per day doing continuous improvement actions in two waves with a peak of 3.62 hours. However, the employees performed an average of 4.61 hours per day during the project. As a result, the number of problems during the project was only 42%, the number estimated by the simulator. The simulator estimated 4.64 problem hours on average, but the company had 1.97 hours of problems (Figure 24). It means the employees more than double the number of hours in continuous improvement, and as a result, they had less than half of the hours of problems in the process.

This result shows the first positive test for the model. Although the positive final test, the model and methodology can receive improvements:

1 - The CI project's first challenge was to follow the schedule suggested by the model. The project responsible should adapt the methodology to guarantee that the employees perform the hours provided by the simulator. In this first test, the managers of the project, motivated by the continuous improvement project and the new actions, used every opportunity to work in continuous improvement activities.

2 - The model can be refined to avoid peaks. Peaks such as the "prob sim" in figure 24 can discredit the model because they are too far from reality.

3 - The test can be longer and provide more data. The project implemented in this work used 100% of real data. The company methodology to gather the data was not adapted to the model's needs. The project responsible can work closer to the company, guide the company's managers to guarantee the quality and integrity of the data

4 - The model can be tested again and adapted to new realities. For confirmation, the author and other researchers can test the model in different processes, from manufacturing to services, from industry to healthcare system. And also with different methodologies of continuous improvement projects. The authors implemented a 5S project in this work, but researchers can practice PDCA, PDSA, lean manufacturing, Six Sigma analysis, and others.

5 - The model can also be improved to include new equations and analyze different points of the project, such as interaction, communication, or employee engagement.

4.2 Third tool - Simulation Continuous Improvement Effect in Participatory Management

4.2.1 Results

The model introduces the first merge of the theory of Woolley (2010) – Collective intelligence Factor in human groups, (Pentland, 2012) – New science of building great teams, and Rutherford A. (2013) – Limits of social mobilization. The result of this discussion is a model able to compare "participatory management" with a "top-down individual management style."

The model integrates the first version of engagement measurement. In the model, the worker's energy represents employee engagement. This energy keeps the agent searching for new improvement opportunities. The model links engagement with the problems. This new link is essential to shift the classic opinion: "More engagement equals more productivity." The model results continue the discussion of the importance of a continuous improvement project from the two previous tools. This importance is due to the capacity of a CIP to impact the management style and engagement.

As presented in section 3.5, the model compared two scenarios, one (operators_1) where the employees can work together due to the "vision" capacity and the other (operators_2) where the employees are working alone (without the "vision" capacity). The results of this model are available in the following paragraphs.

To perform the simulation, the author started using the database from the first model, number of problems equals 2, and after performed ten simulations with different variables to explore different scenarios and explore the relations between the variables. The table below shows the model settings for the ten tests performed with the simulator.

Table 4.1 Model settings

Variable	Value Test#1	Value Test#2	Value Test#3	Value Test#4	Value Test#5	Value Test#6	Value Test#7	Value Test#8	Value Test#9	Value Test#10
Operators1-vision	50	50	50	50	50	50	50	50	50	50
Initial-energy	15	30	15	30	30	50	15	15	15	15
Initial-number-problems	2	2	5	5	10	5	10	2	2	10
Impro_opp_rate	15	15	15	15	15	15	15	15	30	30
Operators1-vision	50	50	50	50	50	50	50	50	50	50
Initial_problems_rate	2	2	2	2	2	2	2	2	2	2
Capacity_to_solve	50	50	50	50	50	50	50	50	50	50
Indiv_capacity	10	10	10	10	10	10	10	10	10	10
Max-number-operators1	30	30	30	30	30	30	30	30	30	30
Dice	60	60	60	60	60	60	60	60	60	60
Operator-energy-gain-from-impro_opp.	50	50	50	50	50	50	50	50	50	50
Initial-number-operators1	20	20	20	20	20	20	20	20	20	20
Show-energy?	false	false	false	false	false	false	false	false	false	false
Operators2-vision?	false	false	false	false	false	false	false	false	false	false
Number of ticks with operator	500	219	500	159	500	5	500	310	500	179
Problems_solved at the last operator	6 522	4 996	11 080	1 910	51 524	4	103 137	4 801	15 719	16 607
Problem solved by operator (average)	0,675	1,361	0,891	0,491	101,326	0,109	205,573	1,072	1,275	4,526

The author worked with three of the model's 11 variables to perform the simulations. The variables used are in red in table 9 (all the variables are better explained in section 3.5.1) :

- **Initial-energy:** The engagement relation in the model. This value defines the engagement level at which the operators will start. With each step made by the operator, he loses an energy point.
- **Initial-number-problems:** The number of problems at the launch of the simulation
- **Impro_opp_rate:** The number of new improvement opportunities created when the probability is positive.

The author performed ten simulations. In the first eight tests, the variables experimented on are "initial energy" and "initial number of problems." In the 9th and 10th tests, the author changed the "impro_opp_rate" variable.

The first test was performed with an initial energy of 15 and an initial number of problems of 2. Each test has 500 ticks (a tick is a measure of time in netlogo). Starting the simulation with quantity "two" as an initial number of problems is a reference from project one actual data (Prob Real Averag. - Figure 20). All the other values are estimations made by the author.

The objective of each test is to find an equilibrium between the populations of problems, improvement opportunities, and operators 1 and 2. Due to its relation with engagement, it is also important to note the role of the variable "Initial_energy."

The figure below shows the result of the first test.

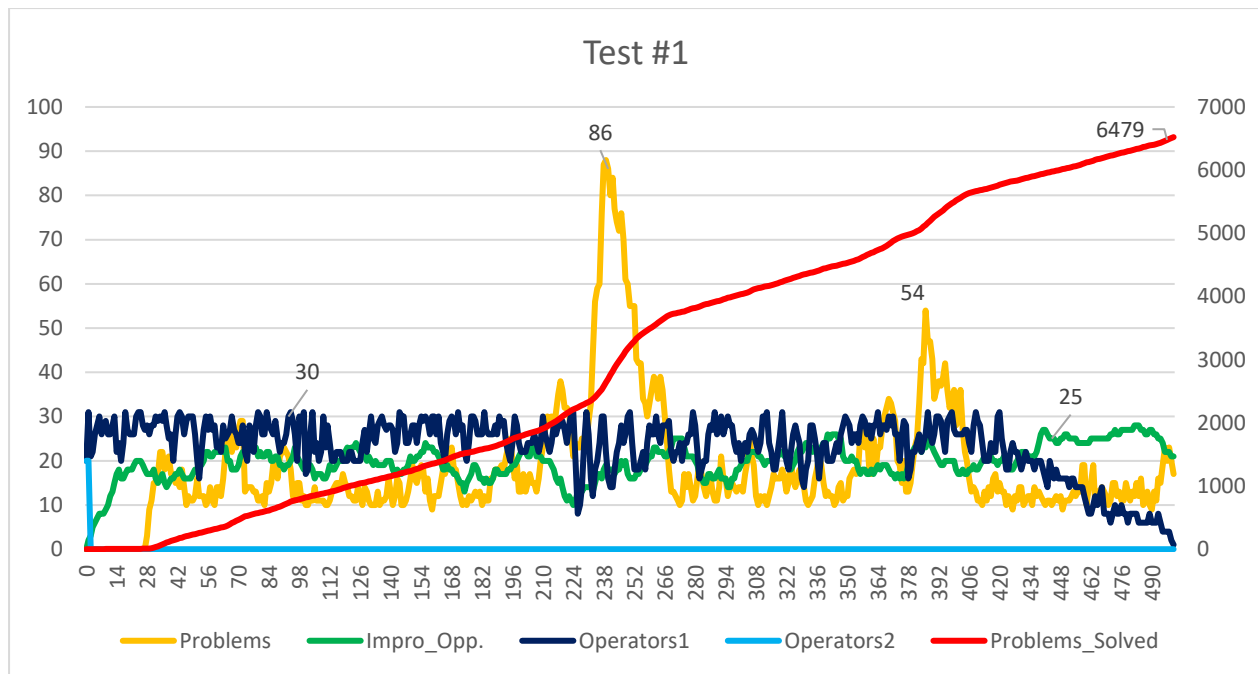


Figure 4.9 Test #1 Participatory management model

The first test was performed with an initial number of problems equal to two and initial energy equal to 15. The graph shows two peaks of problems and the presence of operators1 until the end of the test.

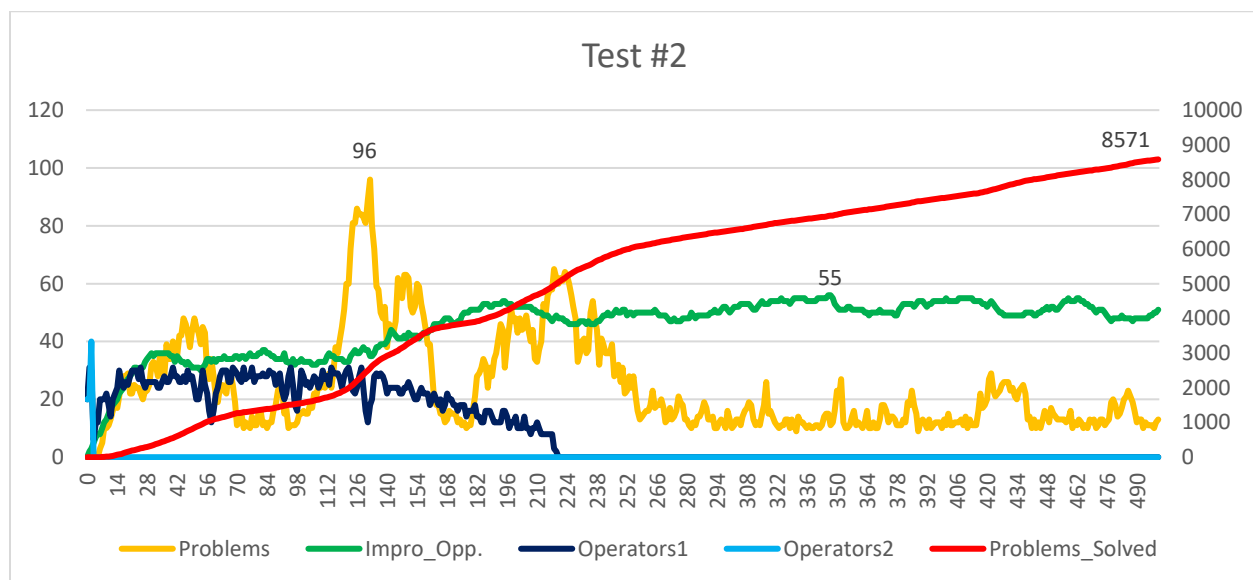


Figure 4.10 Test #2 PM model

It is essential to notice the presence of operators1 because he represents participatory management. As described in the methodology, participatory management is simulated with the variable

"vision." This variable permits the operators close to each other to work together. In the second test, the author increased the variable "Initial_energy" to five, but with more engagement, the number of operators1 reached zero around tick 220. In the next test, the author returned the value of "initial-energy" to 15 and increased the number of problems to 5. The figure below shows the results of test#3.

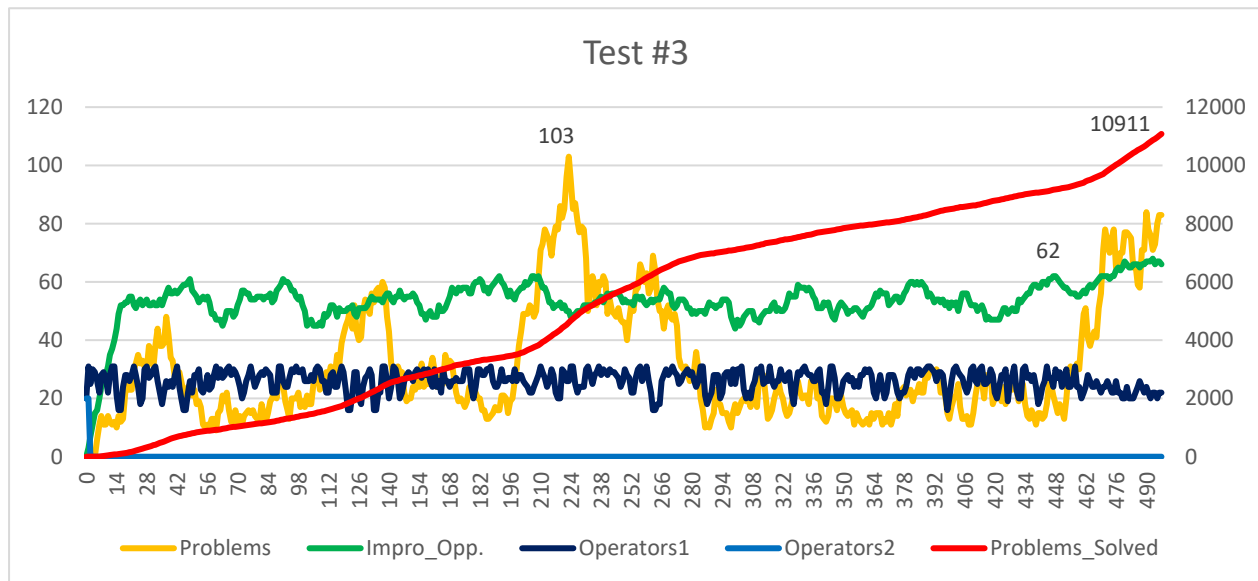


Figure 4.11 Test #3 PM model

Even with the "initial_energy" at 15 again and the number of problems increased to 5, operators1 survived until the tick 500. Furthermore, solved more problems at the end (10.911 in test 3 against 8.571 in test 2). This shows the importance of the number of problems. The slight increase in the number considerably changed the result.

The following result in this section is test number 5. Test number 4 and all other tests are available in the appendix C of this work. Test number 5 increased the Initial_energy and the number of problems, as observed in the figure below.

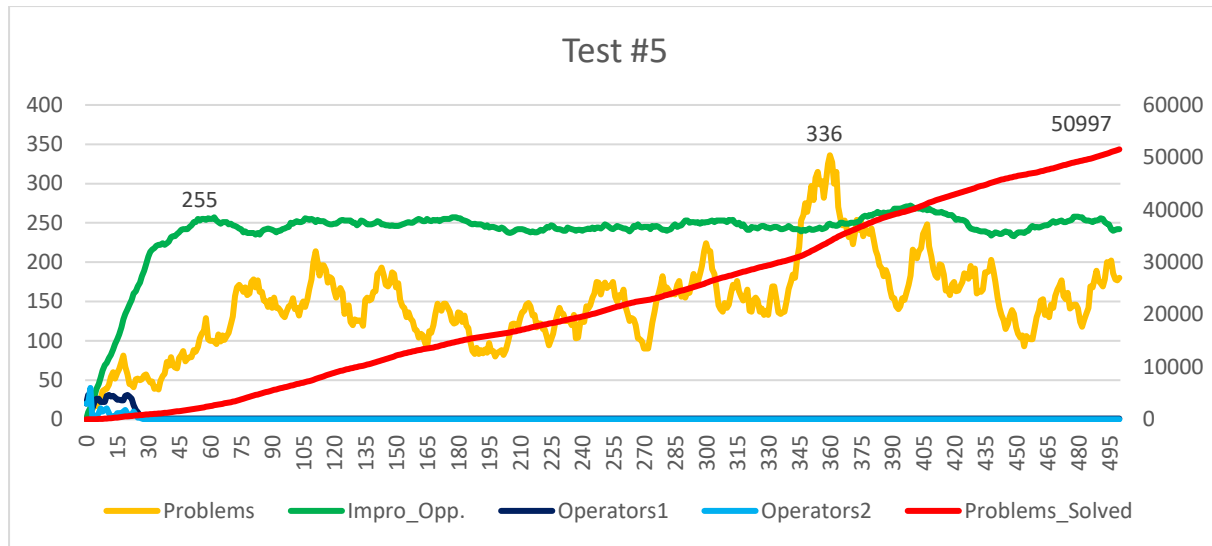


Figure 4.12 Test #5 Pm Model

To perform this test, the author doubled the number of problems and initial energy from test 3. Increasing these two variables impacted the final number of problems solved and improvement opportunities. The "problems solved" total was high five times, and the average of improvement opportunities moved from 62 to 255 on average. On the other side, the number of operators1 was equal to one from tick 30 until the end of the simulation.

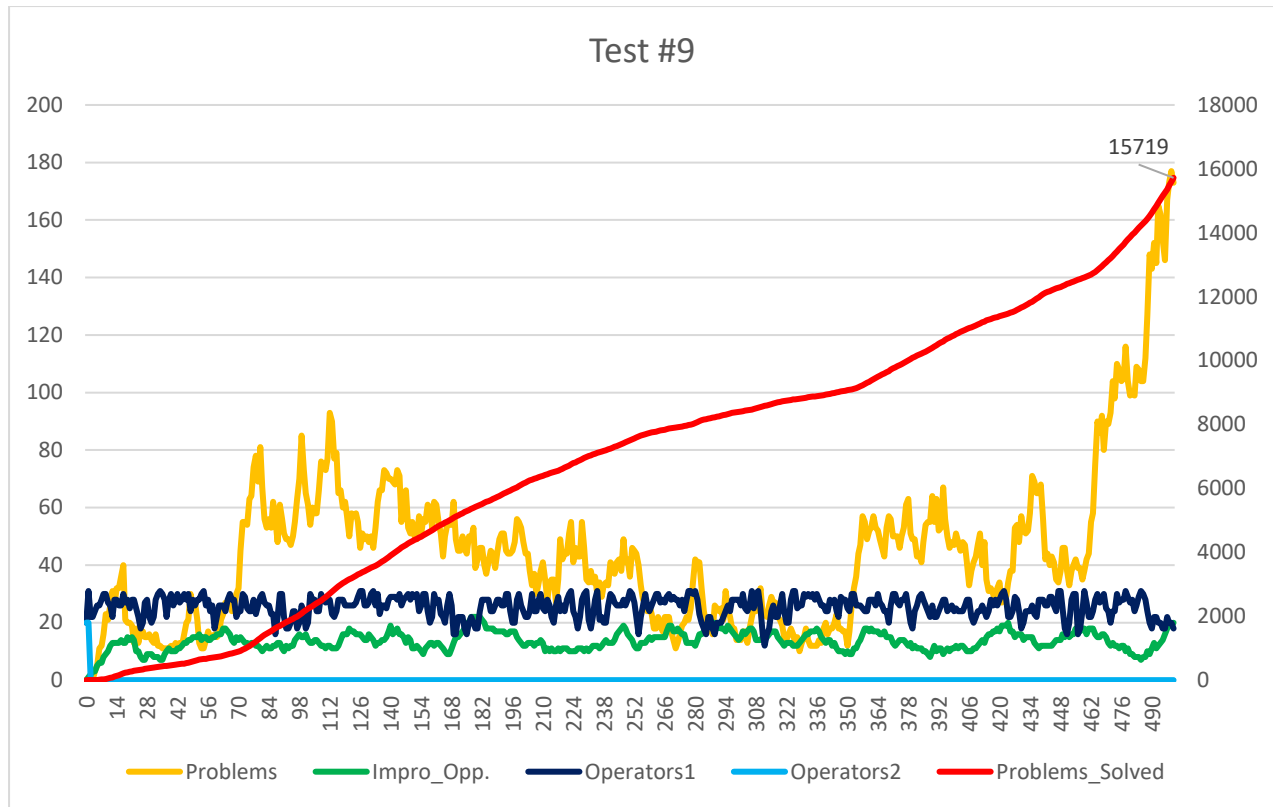


Figure 4.13 Test #9 Pm Model

The two last tests performed in this work focused on the variable "improvement opportunity." Test number 9 used the same values as test 1, Initial energy equals 15, and initial problems equals 2. Nevertheless, the author increased the "improvement_opp_rate" from 15 to 30. Only this change increased the number of "problems solved" from 6.479 to 15.719. One important point to discuss is the reduction in improvement opportunities. During test 1, the average improvement opportunities were 19.6, and during test 9, it was 13.6.

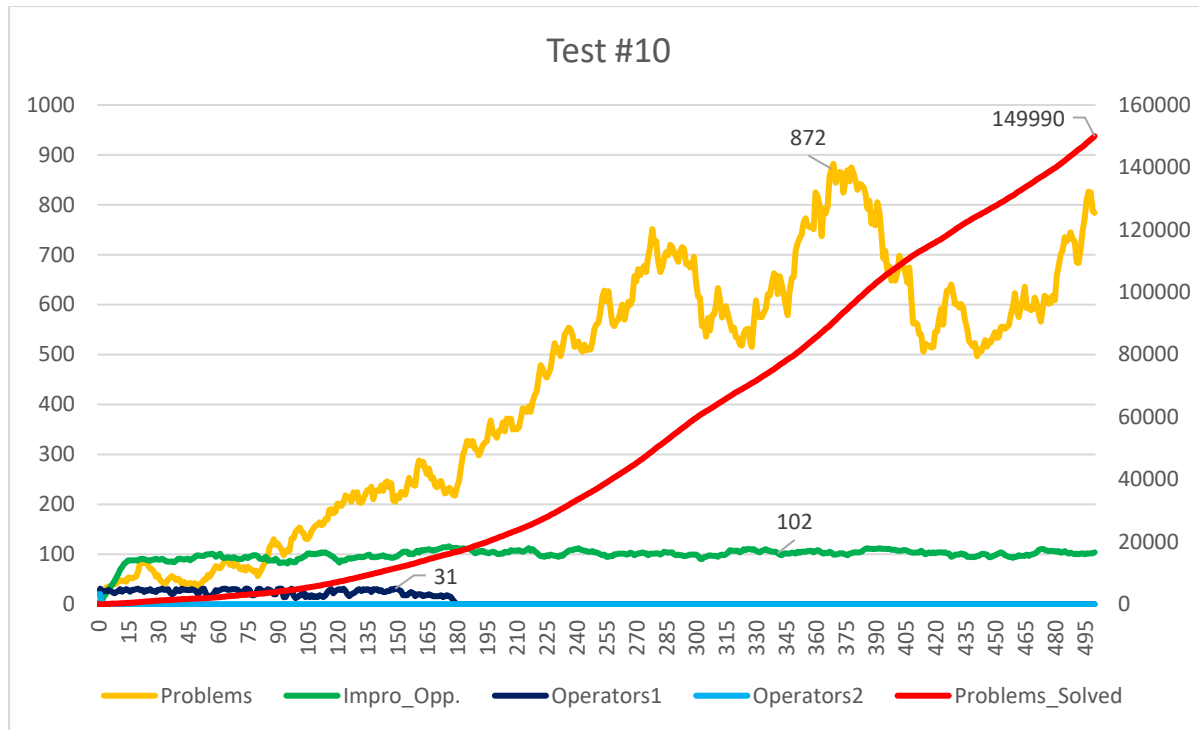


Figure 4.14 Test #10 Pm Model

The final test presented in this work focused again on the improvement opportunities. To perform this test, the author increased the "initial-number-problems." During test number 9, this variable was equal 2. During number 10, the author increased to 10 the value of the initial problems. This change increased the improvement opportunities average by five times and the total of problems solved 9 times.

4.2.2 Conclusion

The work tested the possibility of simulating participatory management with the variables of a continuous improvement project. The multi-agent systems program Netlogo was chosen to simulate the environment due to its characteristic of triggering the next simulation step through the interaction between the agents. The software interphase was simple and practical, which opened the way to perform several tests.

The tests showed the importance of problems and improvement opportunities rate. It is possible to translate these variables into the importance of the employees knowing how to identify a problem and their capacity to perform a problem-solving methodology.

The main comparison made by the model is the efficiency between operators1 and 2. In all tests, operators2 could not find the problems fast enough to keep his energy/engagement. The result is the recurrent low level of operators2 compared with operators1. Operators1, due to the variable "vision," was present until the end of the simulation in five of the ten tests. Also, operators1 had better performance than operators2 in all the ten tests.

The relation between initial energy and the number of operators should be better explored. The initial energy is the engagement level of the worker when he/she starts the project. The higher the engagement, the longer the worker should resist (if the engagement/energy is zero, the agent is deleted in the simulation). However, the tests were not conclusive of this relation.

The next chapter will discuss the results of the three tools presented in this work, build the relations between them and prepare the work for the conclusion.

CHAPTER 5 GENERAL DISCUSSION

The general discussion shows the main results and contributions of this work. The reader will find the global results and the link between the models. To support the discussion, the author answers the questions proposed before and answers five new questions.

5.1 Main results and contributions

This work's main result is a detailed description of the relationship between continuous improvement and three related areas: Productivity, Employee engagement, and Participatory management.

The methodology and the first tool, productivity, shed light on an essential point in the continuous improvement project. "How to define the number of hours necessary for the project?" The tool was tested with actual data from a manufacturing company in Montreal. Although the complexity of the manufacturing industry, the simulator provided a positive answer for its first test. Considering the number of CI hours performed by the employees, the tool simulated the extrapolated number of problems.

The conclusive contribution was a methodology to measure employee engagement. The author did not find an extensive literature review about this significant problem in the industry. To supply this lack of academic research, the work presented a methodology to help the managers measure the gain in engagement and the other financial gain present in a continuous improvement project. The methodology is available for its first next in a company. With this first implementation, the future authors will be able to test the model with actual data and provide an alternative to the classic methods.

The third tool, participatory management, proposed two scenarios. One where the agents can work together and another where they work individually. This tool was programmed with a multi-agent system simulator to compare two scenarios. The simulator showed the importance of participatory management with operators¹ (built with the PM characteristics) solving more problems and being more engaged in all the ten tests made with the simulator.

Section 3.1 presented one main objective and four sub-objectives. The author will first answer the sub-objectives:

- 1 – Establish an adapted Lotka-Volterra model able to measure productivity, employee engagement, and participatory management;

The models are presented in the chapter methodology. The first adapted model estimates the number of hours of continuous improvement necessary to reduce the number of problems on a level determined by the user.

The second model estimates employee engagement of the workers. Furthermore, the third model is a simulator based on the Lotka-Volterra model to understand better the hours of continuous improvement and employee engagement. The model is programmed in a multi-agent simulator.

- 2 - Test the adapted model with the data of a continuous improvement project;

The first model was tested in a manufacturing company in Montreal, Canada. The test and the results are described in the chapter methodology and results.

- 3 - Explore the relationship between the CIP and the three areas previously proposed, comparing the equilibrium of the adapted Lotka-Volterra model;

The results of the first and third models follow the equilibrium of the Lotka-Volterra model (figure 6). This equilibrium is found in figures 22, 25, 26, and 27 for the first model (relation between the worker and problems). And figures 30 and 32 for the third model (relation between the Problems and Improvement opportunities). Although the equilibrium is not perfect, it is the first demonstration of the relation between a continuous improvement project and the Lotka-Volterra model.

- 4 - Explore the problems and discusses how the adapted model proposes a valid alternative.

The models presented are a valid alternative mainly for their characteristics of using continuous improvement data for the estimations. This format avoids the classic method (surveys and questionnaires) and permits a dynamic estimation of the social physics variables.

Furthermore, the methodology presented avoids the normal pressure for productivity. The manager can focus on how many problems are solved and train employees in the process improvement methodology. Similar to employee engagement. The methodology proposed provides a dynamic way to measure employee engagement. This methodology is survey free. The manager does not need to ask their employees if they are engaged (what can cause bias) but evaluate the actions, communication, and results of the process improvement project to find the answer.

The third model's methodology and results are also valid alternatives to measure participatory management. Not only does the Lotka-Volterra model seem an excellent fit to evaluate the equilibrium between problems and improvement opportunities actions, but it also evaluates the team's maturity. A more mature team is better prepared to have participatory management. The conclusion and recommendations address alternatives to use this tool to plan what management style is better for the team.

Primary objective: *Find a relation between the continuous improvement project and social variables.* This objective is addressed in conclusion.

5.2 Questions for discussion

The main question of this work is presented in the introduction as the following:

"How can the continuous improvement methodology impact *productivity*, employee *engagement*, and *participatory management*?"

After the methodologies, tools, and results presented in this work, the author presents three points to discuss the impact of a continuous improvement methodology in: productivity, employee engagement, and participatory management:

1- The variables of the areas studied in this work are present in the continuous improvement methodology.

The variables to measure productivity, employee engagement, and participatory management can be found in a continuous improvement project. The time spent on a task and the overtime are great methods to measure productivity. The variables such as communication, feedback, and the number of ideas are necessary to measure the EE and are available in a continuous improvement project. In the same way, the flow of ideas, the peer pressure, and the number of communities of practice can be extracted from a CIP. This work uses these variables, as explained in the methodology chapter.

2- A continuous improvement project, applying the proper continuous improvement methodology, can function as a mini-lab for the whole company.

The companies can use the continuous improvement methodology to enhance their training with tangible objectives and evaluate the actual management level. This is one of the reasons for the third tool.

3- The continuous improvement methodology can provide the data to empirically measure the typically qualitative areas (employee engagement and participatory management).

Gathering the data for social physics simulation can be long and tumultuous. To help with this task, the managers can build a continuous improvement project and establish fundamental objectives for the company. This project can provide the necessary data for the simulations.

Based on these statements, the work repeats the hypothesis stated in the introduction:

"A CIP can propose a more accurate or new method to measure productivity, employee engagement, and participatory management."

What are the relations between the tools?

The tools follow a line of improvement not just in the processes but also for the employees and direction. With the tool implemented, the manager can provide a new view on the importance of productivity, engage more the employees and adapt his management style for the actual level of the company.

More productivity, more employee engagement. With more employee engagement, the closer to participatory management, the company will be.

What are the relations between the prey in the Lotka-Volterra and the problems in the adapted model?

One hypothesis point is the relation between prey in the general Lotka-Volterra model and problems in the first model presented in this work. The central relationship is the equilibrium between the populations in each sphere. In the LV model, the predator and the prey populations work in equilibrium. In the same way, the workers (doing continuous improvement actions) and the problems according to the author's hypothesis.

This relation has several limitations, not aiming to cover all possible limitations the author lists (x) to start the discussion:

(1) The creation or arrival of new prey is made by the relation between two other animals of the same species. The problem does not need this encounter to arrive. The company's complexity could generate a problem; even with zero problems, a new problem can surge.

(2) The number of preys is limited by food availability, which is unnecessary for the problems.

(3) The existence of the problems is directly linked with the company problem's identification capacity. With more experience and time, the workers can find more problems. So the absolute number of problems depends on the dedication to find them by the company.

What is the impact of the chaotic behavior in the first tool?

As the methodology chapter says, the first and second tools are nonlinear equations. It means that a change in the input will not change the output in the same dimension. With its interaction between two equations, the population model already has this behavior. So changing the input to more than 0.000X can provide a different result.

Also, the model's numerical solution, based on the program ODE45 from Matlab, adds a random factor to the result. So, even running the same input values, the outputs can be different.

These features bring the model to the complexity of the real world. The methodology to find the variable "problems" is simple and direct. However, the work stands for the complexity of a manufacturing system. These two points, the chaotic behavior of the Lotka-Volterra model, plus the random function in the numerical solution, can approach this complex environment.

Did the first tool result prove the link between continuous improvement, Lotka-Volterra, and productivity?

The result of the first tool was positive. Although, more tests are necessary. The test performed by the author considered an extrapolation in the value of problems. Since the number of workers did not follow the simulator's recommendations, extrapolation was the method selected to balance the two populations.

The methodology and the test showed the same variables in the three models: Productivity, continuous improvement, and Lotka-Volterra; also, the author tested these variables with the first tool. To prove the link, the author proposes more tests with more data, following the simulator's recommendations and analyzing the new scenario.

What is the relationship between engagement and the number of operators in the third model?

The third tool, the simulation of participatory management in a Multi-agent systems environment, is also based on the Lotka-Volterra model. The model was coded with the functions of the predator and prey model. The Operators (called workers in the first and second tools) represent the predators, and the problems represent the prey. To improve the model, the author integrated the variable energy (by adding the "Initial-energy" slider in the program - as claimed before, the energy represents employee engagement) and imbued this variable with a death rate. Each movement of the operator will reduce one energy point. If the energy reaches zero, the operator is deleted from the simulation. The operator should find a problem and solve it to receive a new energy shot. Another variable included in this model is the variable called "dice," which is the operator's probability of solving the problems.

Although this balance between the variables, tests 2, 4, and 6 showed contradicting results. The Initial-energy variable was increased, but the number of operators was reduced.

The following chapter will address the conclusion and detail the recommendations for the future of this work.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

To conclude this thesis, the author will review the contributions, the limits of the research, and the recommendations resulting from this work.

The work explains the relationship between continuous improvement projects and the social aspects of productivity, employee engagement, and participatory management. It is based on the adaptation made by the author from the Lotka-Volterra model. With this adaptation, the author proposes three tools:

The first and second tools are programs where the project manager collects the data from a continuous improvement project and simulates the productivity and employee engagement of his team. The author tested the first tool in a company in Montreal, and the data guided the chapter 4 results. These first two tools take in hand a solver called ODE45 from the software Matlab.

The third tool uses a different methodology to simulate the adapted Lotka-Volterra model. This methodology is the multi-agent system simulator with the software Netlogo. This methodology proposes to test the model, not in a numerical way (as performed in the first two models), to avoid the chaotic results from a nonlinear model.

The tests performed by the author in the third model showed the relation between the continuous improvement methodology and the management area, in this case, participatory management.

Based on the literature review, the methodology proposed for the three tools, and the results presented, the author concludes this work by confirming the hypothesis proposed in the introduction and the primary objective. *There is a relationship between the continuous improvement methodology, the Lotka-Volterra, and the areas of productivity, employee engagement, and participatory management.*

6.2 Limitations

The first limitation of this work is the short time available to test the model in a company and have actual data. The COVID pandemic between 2020 and 2021 impeded the implementation and testing of the model in this proper environment. Although the innovation of the idea, gathering data from

a continuous improvement project to simulate social aspects such as participatory management and employee engagement demand a considerable amount of data.

The first tool was tested in a manufacturing company, limiting the results and the environment.

Another limitation is the specific social physics knowledge. The author is a specialist in continuous improvement and simulation. However, the variables from social physics, the standard methodology to calibrate the tools proposed, and the social physics simulation expertise was acquired by research and literature review.

A mathematical model simulates reality. All the models, by definition, are a simplification of reality. Although the author proposes a continuous improvement project as a "mini-lab" for social experiments, the complexity of human behavior and interaction is hardly entirely contemplated.

6.3 Recommendations and future work

The recommendations and suggested future work address previously presented results and limitations.

Results:

Manages the chaotic behavior of the first and second tools. To present a simulation in an industry or service, the stability and steadiness of the results are fundamentals.

- (1) The user can place a restrictor in the program to avoid the randomness function.
- (2) The user can use the methodology, the variables, and a continuous improvement project but solve the model with other mechanisms. Multi-agent system, as used by the author in the third model, is an example. Nevertheless, the user can use a supervised or cluster machine learning method with the data and divide the output into groups such as "actively engaged", "moderated," and "not engaged."
- (3) The user can test the tools in different areas, like the healthcare, public sector, or transport systems. Every area can apply the continuous improvement methodology, so it is necessary to test the model in many places where it is possible.
- (4) Addresses the "Initial-energy" and dice variable. As proposed in Figure 15 - the causal loop for the engagement model, employee engagement should reduce the death rate of the workers. Nevertheless, some tests did not perform with this logic. The user can better calibrate the model,

and work with employee engagement specialists and real data, to better use the variable "dice" in the program.

Limitations:

(5) Work with social sciences, and social physics, specialists to determine the variables and the parameters.

(6) Work with biologists for the improvement of the Lotka-Volterra model and the relation between the increasement of prey and problems.

The future of the work is to keep improving the suggested tool for specific industries and compare it with the classical models, as recommended during the work. Participatory management too can be implemented using the four areas studied (collective intelligence, communities of practice, idea flow, and social pressure) to gather data and simulate the result in a department where these areas are encouraged against departments where they are not. The user can also improve and test the model with new variables, such as happiness or communication.

As the introduction informs, two articles will be submitted to continue this work. The first is based on the second tool presented in this work, the model using the data from a continuous improvement project to estimate the employee engagement level. The proposed authors and title is:

R. de Paula, A. Ben Mosbah, Y. Chinniah, S. Bassetto, "Toward a New Engagement Team Model - Proposition of the Methodology," - To be Submitted

Furthermore, the author proposes a fourth article using the participatory management model presented here (third model). This model can help the company decide which management strategy to apply. This paper will use data from a continuous improvement project. With the project data, the managers can see the actual level of the employees (their knowledge level) to apply participatory management. The proposed authors and title is:

R. de Paula, S. Bassetto, "Using CI data to decide which of the three managements strategy to use" - To be Submitted

REFERENCES

- Alves, A. C., Dinis-Carvalho, J., & Sousa, R. M. (2012). Lean production as promoter of thinkers to achieve companies' agility. In *Learning Organization* (Vol. 19, Issue 3, pp. 219–237). Emerald Group Publishing Limited.
- Anabela C. Alves, José Dinis-Carvalho, and Rui M. Sousa, "Lean production as promoter of thinkers to achieve companies' agility," *Learn. Organ.*, vol. 19, no. 3, pp. 219–237, Apr. 2012.
- Anzanello, M. J., & Fogliatto, F. S. (2011). Learning curve models and applications: Literature review and research directions. In *International Journal of Industrial Ergonomics* (Vol. 41, Issue 5, pp. 573–583).
- Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, 247(4945), 920–924.
- Attridge, M. (2009). Measuring and Managing Employee Work Engagement: A Review of the Research and Business Literature. *Journal of Workplace Behavioral Health*, 24, 383–398.
- Bakker, A. B., & Leiter, M. P. (2015). *Work engagement: a handbook of essential theory and research*. Taylor & Francis. ISBN: 9781136980879
- Bal, M. P., Dóci, E., Lub, X., Rossenberg, Y. van, Nijs, S., Achnak, S., Briner, R., Brookes, A., Chudzikowski, K., Cooman, R. de, & Al, N. E. (2019). Manifesto for the Future of Work and Organizational Psychology. *European Journal of Work and Organizational Psychology*.
- Ball, Philip (2004) *Critical Mass: How One Thing Leads to Another*. Publisher Farrar, Straus and Giroux, ISBN-10 0374281254
- Bernardes, Andrea et al. (2012) Framing the difficulties resulting from implementing a Participatory Management Model in a public hospital. *Revista Latino-Americana de Enfermagem*. 2012, v. 20, n. 6, pp. 1142-1151.
- Bernardes, A., G. Cummings, G., Gabriel, C. S., Martinez Évora, Y. D., Gomes Maziero, V., & Coleman-Miller, G. (2015). Implementation of a participatory management model: analysis from a political perspective. *Journal of Nursing Management*, 23(7), 888–897.

- Bhamu, J., & Sangwan, K. S. (2014). Lean manufacturing: Literature review and research issues. In *International Journal of Operations and Production Management* (Vol. 34, Issue 7, pp. 876–940). Emerald Group Publishing Ltd.
- BlessingWhite Research. (2011). Employee Engagement Report 2011 Beyond the numbers: A practical approach for individuals, managers, and executives. In *BlessingWhite - Leadership Development and Employee Engagement*.
- Briner, R. B. (2014). What is employee engagement and does it matter? An evidence-based approach. *The future of engagement thought piece collection*, Institute for Employment Studies. p51.
- Briner, R. B., Denyer, D., & Rousseau, D. M. (2009). Evidence-Based Management: Concept Cleanup Time? *Academy of Management Perspectives*, 23(4), 19–32.
- Buckingham, M., & Coffman, C. (2014). *Buckingham, M., & Coffman, C. (2014). First, break all the rules: What the world's greatest managers do differently*. Gallup Press; Har/Psc edition.
- Chapman, R., & Hyland, P. (2004). Complexity and learning behaviors in product innovation. *Technovation*, 24(7), 553–561.
- Chapman, R., & Hyland, P. (2004). Complexity and learning behaviors in product innovation. *Technovation*, 24(7), 553–561.
- Christian, M. S., Garza, A. S., & Slaughter, J. E. (2011). Work Engagement: A Quantitative Review and Test of Its Relations with Task and Contextual Performance. *Personnel Psychology*, 64(1), 89–136.
- Christopher Marquis, András Tilcsik (2016) Institutional Equivalence: How Industry and Community Peers Influence Corporate Philanthropy. *Organization Science* 27(5):1325-1341.
- Coleman, P. T. (2004). Implicit Theories of Organizational Power and Priming Effects on Managerial Power-Sharing Decisions: An Experimental Study. In *Journal of Applied Social Psychology* (Vol. 34, Issue 2, pp. 297–321). Blackwell Publishing Ltd.
- Coye, R. W., & Belohlav, J. A. (1995). An Exploratory Analysis of Employee Participation. *Group & Organization Management*, 20(1), 4–17.

- Cropanzano, R., & Mitchell, M. S. (2005). Social Exchange Theory: An Interdisciplinary Review. *Journal of Management*, 31(6), 874–900.
- Dormand, J. R., & Prince, P. J. (1980). A family of embedded Runge-Kutta formulae. *Journal of Computational and Applied Mathematics*, 6(1), 19–26. [https://doi.org/10.1016/0771-050X\(80\)90013-3](https://doi.org/10.1016/0771-050X(80)90013-3)
- Frayret, J.-M. (2011). Multi-Agent System Applications in the Forest Products Industry. *Journal of Materials Processing Technology*, 1(2), 15–29.
- Freudenberger, H. J. (1974). Staff Burn-Out. *Journal of Social Issues*, 30(1), 159–165. <https://doi.org/10.1111/j.1540-4560.1974.tb00706.x>
- Fuller, R. (2014). A Primer on Measuring Employee Engagement. In *Harvard Business Review*. <https://hbr.org/2014/11/a-primer-on-measuring-employee-engagement>
- Gallup. (2017). *State of the American Workplace*. Available on: <https://www.gallup.com/workplace/238085/state-american-workplace-report-2017.aspx>
- Georganas, S., Tonin, M., Vlassopoulos, M. (2015) Peer pressure and productivity: The role of observing and being observed. *Journal of Economic Behavior & Organization*
- Greasley, A. (2009). *Operations management* (2nd ed). John Wiley & Sons.
- Gutot, S. (2011). The Instrumentalization of Participatory Management in Protected Areas: The ethnicization of participation in the Kolla-Atacameña Region of the Central Andes of Argentina and Chile. *Journal of Latin American Geography*, 10(2), 9–36.
- Horn, J., Rosenband, L. N., & Smith, M. R. (2010). Reconceptualizing the Industrial Revolution. In *Dibner Institute studies in the history of science and technology*. MIT Press.
- Jeon, S. M., & Kim, G. (2016). A survey of simulation modeling techniques in production planning and control (PPC). In *Production Planning and Control* (Vol. 27, Issue 5, pp. 360–377). Taylor and Francis Ltd.
- Kahn, W. A. (1990). PSYCHOLOGICAL CONDITIONS OF PERSONAL ENGAGEMENT AND DISENGAGEMENT AT WORK. *Academy of Management Journal*, 33(4), 692–724.
- Kan, S. (2002). *Metrics and Models in Software Quality Engineering*. Addison-Wesley Professional; 2nd edition (September 16, 2002).

- Krafcik, J. F. (1988). Triumph of the lean production system. *Sloan Manage. Rev.*, 30(1), 41–52.
- Lagarias, J. C., Reeds, J. A., Wright, M. H., & Wright, P. E. (1998). Convergence Properties of the Nelder--Mead Simplex Method in Low Dimensions. *SIAM Journal on Optimization*, 9(1), 112–147.
- Lesener, T., Gusy, B., Jochmann, A., & Wolter, C. (2020). The drivers of work engagement: A meta-analytic review of longitudinal evidence. *Work & Stress*, 34(3), 259–278.
- Little, B., & Little, P. (2006). Employee Engagement: Conceptual Issues. *Journal of Organizational Culture, Communications and Conflict; Arden*, 10(1), 111–120.
- L. Weber, “A Contribution To Goodwin’s Growth Cycle Model From A System Dynamics Perspective,” presented at the The 23rd International Conference of the System Dynamics Society, 2005.
- Maslach, C. (1976). *Burned-Out* (Vol. 9). Human Behavior journal, 16-22
- Maslach, C. (1998). *A Multidimensional Theory of Burnout*, Human Behavior journal (pp. 68–85).
- Maslach, C., & Jackson, S. E. (1981). The measurement of experienced burnout. *Journal of Organizational Behavior*, 2(2), 99–113.
- Maslach, C., Schaufeli, W. B., & Leiter, M. P. (2001). Job Burnout. *Annual Review of Psychology*, 52(1), 397–422.
- Maslow, A. H. (1943). A theory of human motivation. *Psychological Review*, 50(4), 370–396.
- Maslow, A. H. (1954). *Motivation and personality*. Harpers.
- MDPI AG. (2021). *Nonlinear differential equations and dynamical systems*. Retrieved 2022, from <http://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=5937.29167391.79108938&epcusercontent=s8491974&db=5937>.
- Miscikowski, D. K., & Stein, E. W. (2006). Empowering employees to pull the quality trigger. *Quality Progress*, 39(10), 43–48.
- Moore, D.A. and Tenney, E.R. (2012), "Time Pressure, Performance, and Productivity", Neale, M.A. and Mannix, E.A. (Ed.) *Looking Back, Moving Forward: A Review of Group and Team-*

Based Research (Research on Managing Groups and Teams, Vol. 15), Emerald Group Publishing Limited, Bingley, pp. 305-326.

Morgan, G. (1986). *Images of Organization*. Sage Publications.

Murray, J. D. (2002). Mathematical Biology I. An introduction. In *Interdisciplinary Applied Mathematics* (Vol. 17).

Pentland, A. (2012, April). *The New Science of Building Great Teams*. <https://hbr.org/2012/04/the-new-science-of-building-great-teams>

P. Leitão, “Agent-based distributed manufacturing control: A state-of-the-art survey,” *Eng. Appl. Artif. Intell.*, vol. 22, no. 7, pp. 979–991, Oct. 2009.

Principles of Economics, University of Minnesota, 2016. Available at:

<https://open.lib.umn.edu/principleseconomics/chapter/3-3-demand-supply-and-equilibrium/>

Quesnay, F. (1766). Analyse de la formule arithmétique du Tableau Economique de la distribution des dépenses annuelles d’une nation agricole. *Journal de l’agriculture, Du Commerce et Des Finances*, 2(juin 1766), 11–41.

Reeves, B., & Read, J. L. (2009). Total Engagement: Using Games and Virtual Worlds to Change the Way People Work and Businesses Compete. *Harvard Business Press*.

Reid, R. A. (2006). Productivity and quality improvement: an implementation framework. *International Journal of Productivity and Quality Management*, 1(1-2), 26-36.

Restrepo, D., Charron-Latour, J., Pourmonet, H., & Bassetto, S. (2016). Seizing opportunities for change at the operational level. *International Journal of Health Care Quality Assurance*, 29(3), 253–266.

Saks, A. M. (2006). Antecedents and consequences of employee engagement. *Journal of Managerial Psychology*, 21(7), 600–619.

Schafer, R. (2011). What Is a Savitzky-Golay Filter? [Lecture Notes]. *IEEE Signal Processing Magazine*, 28(4), 111–117.

Schäfer, Lukas & Albrecht, Stefano. (2019). *Curiosity in Multi-Agent Reinforcement Learning*.

DOI: 10.13140/RG.2.2.12795.46886.

- Senge, P. (1990). *The Fifth Discipline: The Art & Practice of the Learning Organization*. Currency.
- Setterfield, Mark. "Supply and Demand in the Theory of Long-run Growth: introduction to a symposium on demand-led growth." (2003): 23-32.
- Shampine, L. F., & Reichelt, M. W. (1997). The MATLAB ode suite. *SIAM Journal of Scientific Computing*, 18(1), 1–22.
- Sharot, T. (2011). The optimism bias. In *Current Biology* (Vol. 21, Issue 23). Cell Press.
- Silver, N. (2012). *The Signal and the Noise: Why So Many Predictions Fail-but Some Don't*. Penguin Group.
- Singh, J., & Singh, H. (2015). Continuous improvement philosophy – literature review and directions. *Benchmarking*, 22(1), 75–119.
- Sink, D. S. (1985). *Productivity management: planning, measurement and evaluation, control, and improvement*. Wiley.
- Sink, D. S., & Tuttle, T. C. (1989). *Planning and measurement in your organization of the future*. Industrial Engineering and Management Press.
- S. M. Jeon and G. Kim, "A survey of simulation modeling techniques in production planning and control (PPC)," *Prod. Plan. Control*, vol. 27, no. 5, pp. 360–377, Apr. 2016.
- Surowiecki, J. (2005). *The Wisdom of Crowds*. Anchor; Reprint edition (Aug. 16 2005).
- Tangen, S. (2005). Demystifying productivity and performance. *International Journal of Productivity and Performance Management*, 54(1), 34–46.
- Tharumarajah, A., Wells, A. J., & Nemes, L. (1996). Comparison of the bionic, fractal and holonic manufacturing system concepts. *International Journal of Computer Integrated Manufacturing*, 9(3), 217–226.
- Wheatley, M. J., & Kellner-Rogers, M. (n.d.). *Bringing Life to Organizational Change*.
- White House Conference on Productivity (1983 : Washington, D. C.). (1984). *White House Conference on Productivity: Report to the President of the United States on Productivity Growth, a Better Life for America : Together with the Reports of the Preparatory Conferences on Capital Investment, Human Resources, Government Organizati.*

- Womack, J. P., Jones, D. T., & Roos, D. (2007). *The Machine That Changed The World: How Japan's Secret Weapon In The Global Auto Wars Will Revolutionize Western Industry*. Free Press.
- Woodruffe, C. (2006). The crucial importance of employee engagement. *Human Resource Management International Digest*, 14(1), 3–5.
- Wright, T. P. (1936). Factors Affecting the Cost of Airplanes. *Journal of the Aeronautical Sciences*, 3(4), 122–128.
- Zangwill, W. I., & Kantor, P. B. (1998). Toward a Theory of Continuous Improvement and the Learning Curve. *Management Science*, 44(7), 910–920.
- Zangwill, W. I., & Kantor, P. B. (2000). The learning curve: a new perspective. *International Transactions in Operational Research*, 7(6), 595–607.

APPENDIX A MATLAB CODE FOR THE FIRST MODEL

Section 1 : Extraire les données

```
% % % a=input('jusqu''a quelle ligne voulez vous
aller dans le fichier excel:\n','s'); a='58';
ligne1= ['A2:A' a]; ligne2= ['B2:B' a]; ligne3=
['C2:C' a]; ligne4= ['D2:D' a]; % temps1 =
xlsread('extract_file.xlsx',1,ligne1);

%           temps2           =
xlsread('extract_file.xlsx',1,ligne3);
%           y1           =
xlsread('extract_file.xlsx',1,ligne2);
%           y2           =
xlsread('extract_file.xlsx',1,ligne4);

seuil1=1.7*m
ean(y1);
seuil2=1.7*m
ean(y2);
y1(y1>
seuil1)=seuil1;
y2(y2>
seuil2)=seuil2;

prob_exp=sgolayfilt(y1,3,7);
wk_exp=sgolayfilt(y2,3,7);

m=length(prob_exp);
a=mean(prob_exp)*ones(m,1);
b=mean(wk_exp)*ones(m,1);
```

```

temps1=(1:m)
';
temps2=temps
1;

% premiere figure : affiche les données
experimentales et données filtrées figure
plot(temps1,prob_exp,temps1,y1,temps1,wk_exp,temps1,
y2)

title('données experimentales vs données
filtrées')
legend('prob_filt','prob_brut','wk_filt','wk_bru
t') xlabel('temps(jour)') ylabel('heures de
travail') figure % deuxieme figure : affiche
les courbes filtrées ainsi que leur moyennes
plot(temps1,prob_exp,temps1,a,temps1,wk_exp,temp
s1,b) legend('prob_filt','moyenne de
prob','wk_filt','moyenne de wk') xlabel('temps')
ylabel('heures')

```

Section 2 : Calcul des parametres en fonction des donnees experimentales

```

x = fminsearch('calcul',[randi([ floor(min(prob_exp))
floor(max(prob_exp)) ])/max(prob_exp), randi([
floor(min(prob_exp)) floor(max(prob_exp))
])/max(prob_exp), randi([ floor(min(wk_exp))
floor(max(wk_exp)) ])/max(wk_exp), randi([
floor(min(wk_exp)) floor(max(wk_exp))
])/max(wk_exp), prob_exp(1), wk_exp(1)]); [t,b] =
equadif(x(1),x(2),x(3),x(4),x(5),x(6)); fprintf('les
nouveaux parametres sont %1.3f',x) pbmoy=
mean(prob_exp)*ones(length(temps1),1);
wkmoy=mean(wk_exp)*ones(length(temps2),1);
pbmoy_mod= mean(b(:,1))*ones(length(t),1);
wkmoy_mod=mean(b(:,2))*ones(length(t),1);
fprintf('la valeur de pb exp moy est
%1.3f',mean(prob_exp)) fprintf('la valeur de wk exp
moy est %1.3f',mean(b(:,1))) fprintf('la valeur de pb

```

```

exp moy est %1.3f',mean(wk_exp)) fprintf('la valeur
de pb sim moy est %1.3f',mean(b(:,2)))

% tracage des plot de workers et problem figure title('courbes avec
parametres optimale obtenues par simulation vs exp(+leur moyennes)')
plot(temps1,prob_exp,'b-.',temps2,wk_exp,'-
.r',t,b(:,1),t,b(:,2),t,pbmoy,t,wkmoy,t,
legend('pb_filt','wk_filt','pb_simulé','wk_simulé','moy_(pbexp)','m
oy_(wk-exp)','moy_(pb-sim)','moy_(wk-sim)')

```

```

Exiting: Maximum number of function evaluations
has been exceeded          - increase MaxFunEvals
option.          Current function value: 12.422596

```

```

les nouveaux parametres sont 0.928les nouveaux
parametres sont 0.074les nouveaux parametres sont
0.348les nouveaux parametres sont

```

```

0.500les nouveaux parametres sont 21.920les nouveaux
parametres sont

```

```

5.658la valeur de pb exp moy est 11.949la valeur de wk
exp moy est

```

```

1.052la valeur de pb exp moy est 18.568la valeur de pb
sim moy est

```

```

18.569

```

Section 3 : trouver une nouvelle loid e lotka voltera

```

global          x0          goal          x0(1)=prob_exp(end);
x0(2)=wk_exp(end); % % % % goal=input('entrez la
nouvelle valeur moyenne de probleme'); goal=1; y =
fminsearch('chercher',x); fprintf('les nouveaux
parametres sont %1.3f',y)

[t2,b2]          =
equadif(y(1),y(2),y(3),y(4),y(5),y(6));
pbmoy_mod2=
mean(b2(:,1))*ones(length(t2),1);
wkmoy_mod2=mean(b2(:,2))*ones(length(t2),1);

fprintf('la nouvelle valeur de pb sim moy est %1.3f',mean(b2(:,1)))

```

```

fprintf('la nouvelle valeur de wk sim moy est %1.3f',mean(b2(:,2)))
figure title('comparaison entre ancienne simulation et nouvelle
simulation                               (nouveaux                parametres)')
plot(t,b(:,1),t,b(:,2),t,pbmoy_mod,t,wkmoy_mod,t2,b2(:,1),t2,b2(:,2)
),t2,pbmoy_mod2,          legend('pb-sim-old','wk-sim-old','old-avg-
pb','old-avg-wk','pb-simnew','wk-sim-new','new-avg-pb','new-avg-
wk')

```

les nouveaux parametres sont 0.558les nouveaux
parametres sont 0.090les nouveaux parametres sont
0.383les nouveaux parametres sont

0.368les nouveaux parametres sont 24.470les nouveaux
parametres sont

6.565la nouvelle valeur de pb sim moy est 1.451la
nouvelle valeur de wk sim moy est 9.260

APPENDIX B NETLOGO CODE FOR THE THIRD MODEL

```

globals [ failures a

    list_energy

    Division1      ;; agentset containing the patches that are roads

    Division2

    Division3

    Division4

    problems_solved

    ] ;; keep track of how much failures there is

;; Impro_Opp. and operators1 are both breeds of turtle.

breed [Impro_Opp. a-Impro_Opp.] ;; Impro_Opp. is its own plural, so we use "a-Impro_Opp." as the singular.

breed [operators1 operator1]

breed [operators2 operator2]

breed [operators3 operator3]

breed [operators4 operator4]

breed [problems problem]

turtles-own [

    energy

    Impro_Opp._food

    nearest-Impro_Opp._food

] ;; both operators1 and Impro_Opp. have energy

patches-own [countdown]

```

```

problems-own [ ]

to setup

  ca

  set Division1 patches with
    [ pxcor > -26 and pycor > -1 ]

  set Division2 patches with
    [ pycor < 0 and pxcor < 26 ]

  ; set Division3 patches with
  ;[ pycor < 0 and pxcor > -1 ]

  ; set Division4 patches with
  ;[ pycor > -1 and pxcor < 0 ]

  Ask division1 [ set pcolor green ]
  Ask division2 [ set pcolor blue ]
  ;Ask division3 [ set pcolor red ]
  ;Ask division4 [ set pcolor magenta ]

  set-default-shape operators1 "person business"

  create-operators1 initial-number-operators1 ;; create the operators1, then initialize their
  variables

  [
    set color orange

    set size 2 ;; easier to see

    set energy Initial-energy

    setxy 0 12
  ]

  set-default-shape operators2 "person business"

```

create-operators2 initial-number-operators1 ;; create the operators1, then initialize their variables

```
[
  set color black

  set size 2 ;; easier to see

  set energy Initial-energy

  setxy 0 -12
]
```

;set-default-shape operators3 "person business"

; create-operators3 initial-number-operators1 ;; create the operators1, then initialize their variables

```
:[
  ; set color orange + 1

  ;set size 2 ;; easier to see

;  set energy Inicial-energy

;  setxy 0 0

; ]
```

display-labels

reset-ticks

end

to go

if not any? turtles [stop]

set-default-shape problems "exclamation"

create-problems initial-number-problems

```
[
```

```

set color red

set size 1.5 ;; easier to see

set label-color blue - 2

setxy random-xcor random-ycor

if random 100 > Impro_opp_rate [
  set breed Impro_Opp.

  set color white

  set size 1.5 ;; easier to see

  set label-color blue - 2

  set energy Initial-energy
]

scared-check

; set-default-shape Impro_Opp. "Star"

;create-Impro_Opp. count problems * Impro_opp_rate ;; create the Impro_Opp., based on
the number of failures

; [

; set color white

; set size 1.5 ;; easier to see

; set label-color blue - 2

; set energy Inicial-energy

; setxy random-xcor random-ycor

; ]

ask problems [

  ;set energy energy - 1 ;; deduct energy for problems only if failures? switch is on

  Solve-problem

```

```

    reproduce-problems
    more-problems
]
ask Impro_Opp. [
    set energy energy - 1 ;; deduct energy for Impro_Opp. only if failures? switch is on
    death
]
ask operators1 [
    pen-down
    move
    set energy energy - 1 ;; operators1 lose energy as they move
    catch-Impro_Opp.
    death
    reproduce-operators1
    set energy (energy / count operators1)
]
ask operators2 [
    pen-down
    move
    set energy energy - 1 ;; operators2 lose energy as they move
    catch-Impro_Opp.
    death
    reproduce-operators1
    set energy (energy / count operators2)
]

```

```
]
do-plot
tick
display-labels
end
to scared-check
  ask operators1 [
    seek-Impro_Opp._food
    ifelse any? Impro_Opp._food
      [run-toward]
      [move]
  ]
  if operators2-vision? [
    ask operators2 [
      seek-Impro_Opp._food
      ifelse any? Impro_Opp._food
        [run-toward]
        [move]
    ]
  ]
end
to more-problems
  if count problems < 10 [ hatch initial-number-problems ]
end
```

```

to seek-Impro_Opp._food

set Impro_Opp._food Impro_Opp. in-radius operators1-vision
end

to run-toward ;;Make a operators1 chase the idea closest to it.

  set nearest-Impro_Opp._food min-one-of Impro_Opp._food [distance myself]

  face nearest-Impro_Opp._food
end

to move ;; turtle procedure

ask operators2

[
  ifelse xcor > -26 and ycor < -1 [ fd 1]
    [ rt 180 fd 1]
]

ask operators1

[
  ifelse xcor > -26 and ycor > 0 [ fd 1]
    [ rt 180 fd 1]
]

end

to reproduce-problems

if random 2 * 100 < dice [ ;;;;; throw "dice" to see if you will reproduce

  hatch Initial_Problems_Rate ;; hatch an offspring and move it forward 1 step
]

```

```

end

to reproduce-operators1 ;; operator procedure

  ifelse count operators1 <= Max-number-operators1 [if (count Impro_Opp. / count
operators1) < Indiv_Capacity

                                [ hatch 1 ]]

  [ stop ]
end

to catch-Impro_Opp. ;; operator procedure

  let prey one-of Impro_Opp.-here          ;;;; grab a random Impro_Opp.

                                ; Impro_Opp.-here = So if we have one or more turtles
(Impro_Opp.) in one patch, all the turtles in this patch will do this action. (prey

  if prey != nobody                    ;; did we get one? if so,

  [ ask prey [ die ]                  ;; kill it

    set energy energy + operator-energy-gain-from-Impro_Opp. ;; get energy from eating

  ]

end

to Solve-problem

  let b one-of problems

  ifelse random 2 / 100 <= Capacity_to_solve [if b != nobody

    [ask b [

      set problems_solved problems_solved + 1

      die

    ]

    set energy energy + 0

  ]] []

```

```

end

to death ;; turtle procedure

    ;; when energy dips below zero, die

    if energy < 0 [ die ]

end

to display-labels

    ask turtles [ set label "" ]

    if show-energy? [

        ask operators1 [ set label round energy ]

        ask operators2 [ set label round energy ]

        ask Impro_Opp. [ set label round energy ]

    ]

end

;;

;; Plotting Procedure

;;

to do-plot

    set-current-plot-pen "Problems_solved"

    ;plot count problems_solved

    ;;Set operators1 with [ breed != energy ]

    ;set-current-plot "Average Energy" ;;this plots the total energy of Impro_Opp., and of
operators1

    ;set-current-plot-pen "operators1"

    ;ifelse any? operators1

    ; [ plot mean [ energy ] of operators1 ]

    ;[ plot 0 ]

```

```
; set-current-plot-pen "Impro_Opp."  
; ifelse any? Impro_Opp.  
; [ plot mean [ energy ] of Impro_Opp. ]  
; [ plot 0 ]  
end
```

APPENDIX C TESTS RESULTS FOR THIRD MODEL

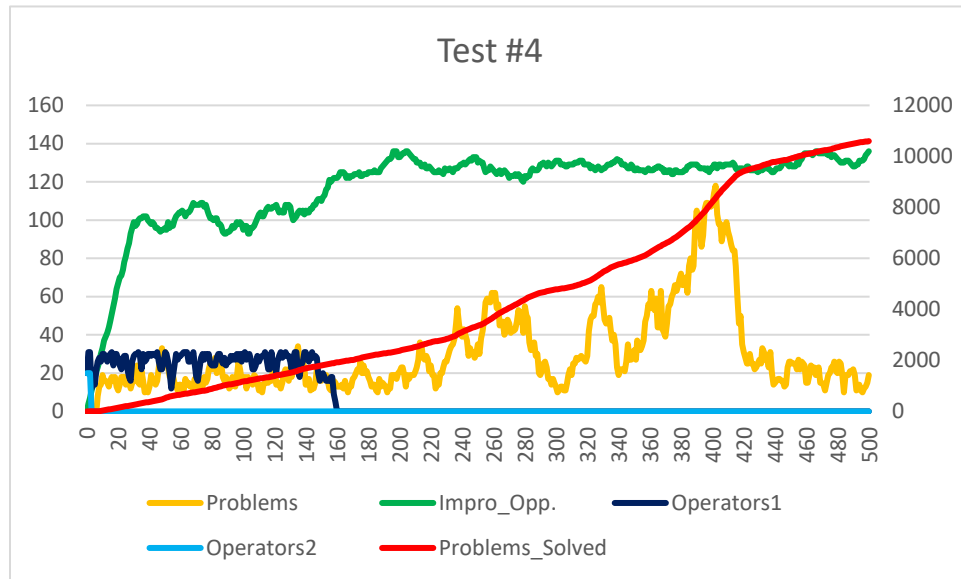


Figure C.1 Test #4 Pm Model

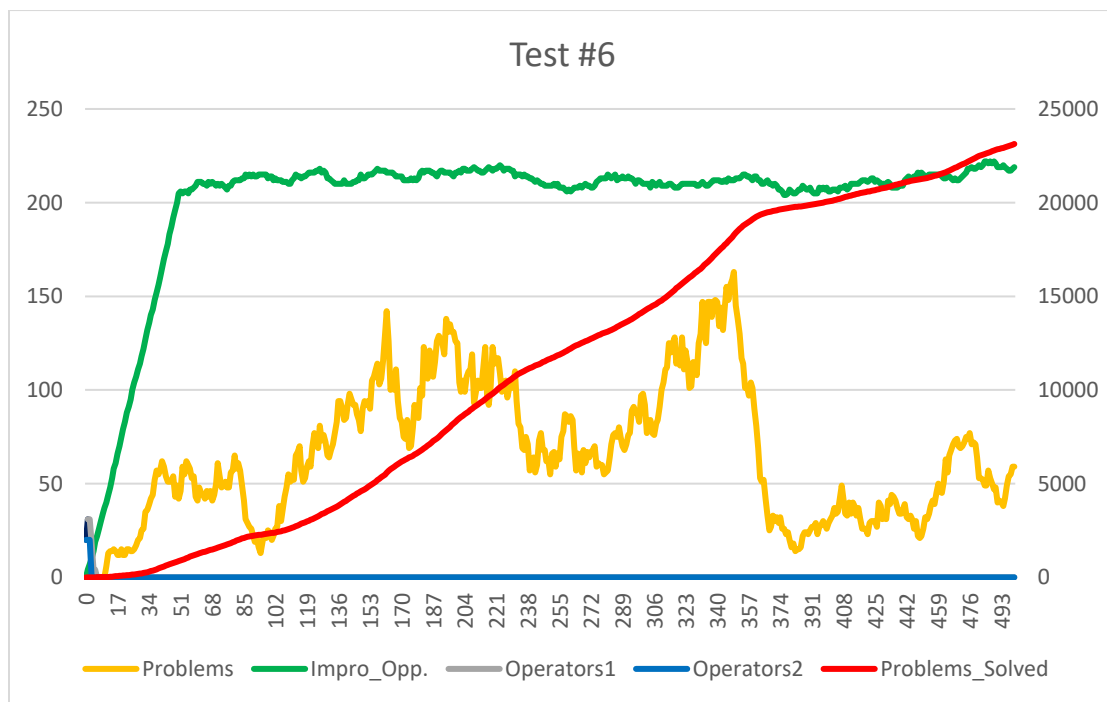


Figure C.2 Test #6 Pm Model

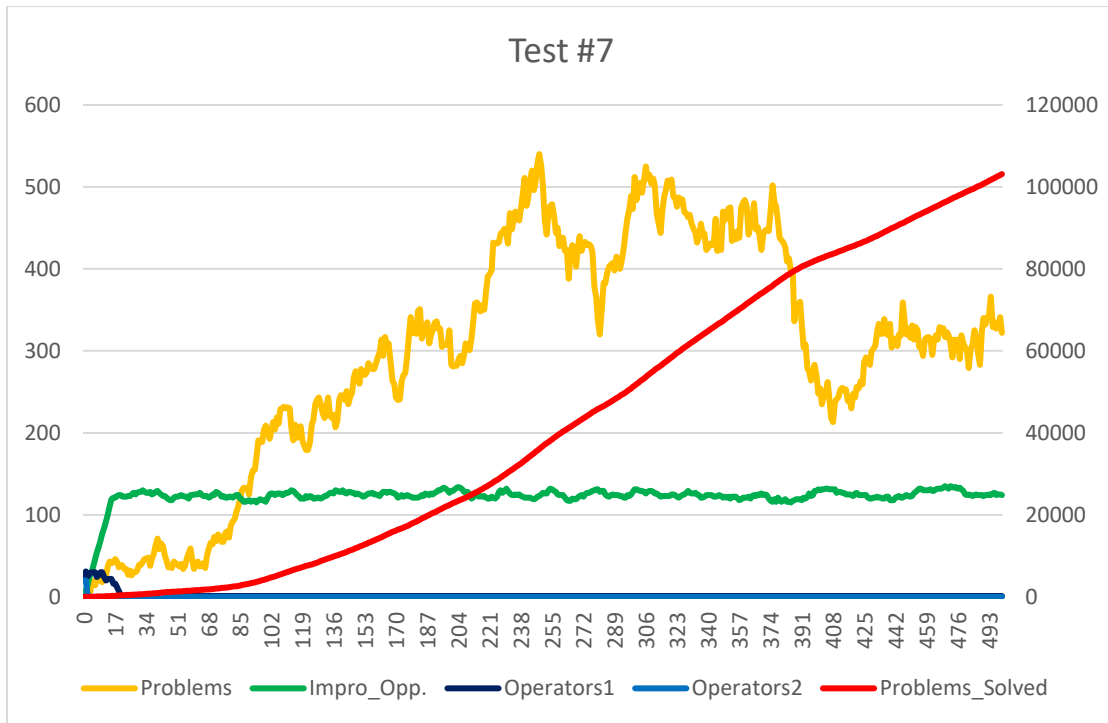


Figure C.3 Test #7 Pm Model

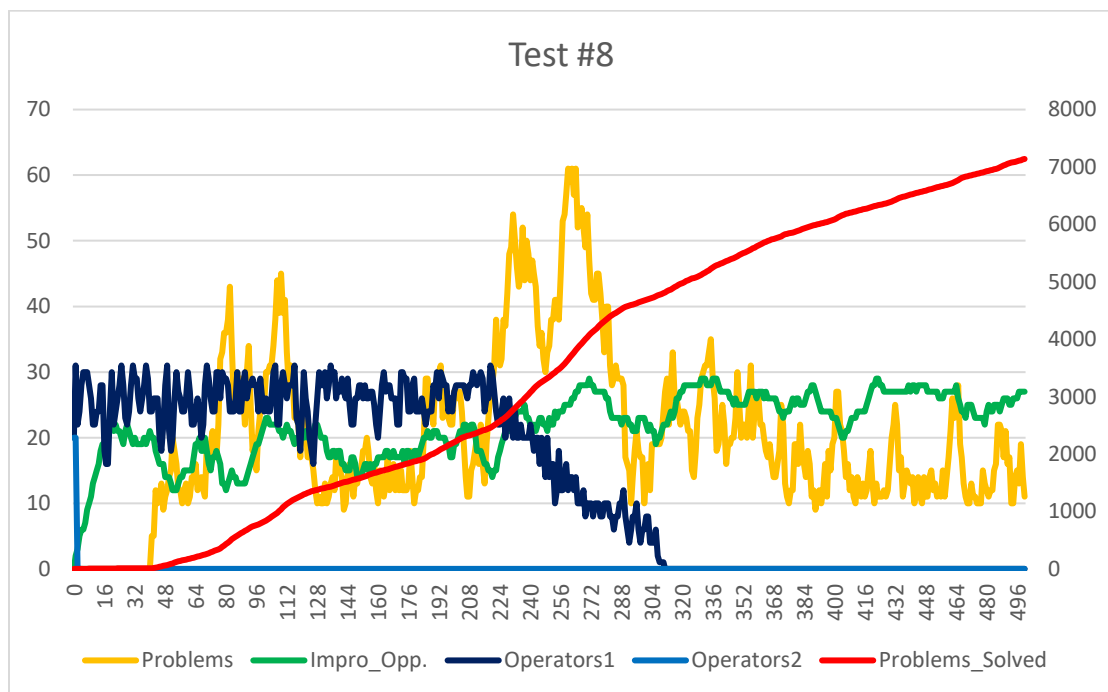


Figure C.4 Test #8 Pm Model