An Optimization of Inventory Model at Seaports Using a System Dynamics Approach

By

Moosavihaghighi Mohammadhashem and Semail Ulgen

Department of Industrial Engineering, Antalya Bilim University, Antalya, Turkey

Razmjooei Damoon

Department of Maritime Transportation, Faculty of Economics and Management, Khorramshahr University of Marine Science and Technology, Iran

Tahamtani Mohammad

Management Dept., Faculty of Economics and Management, University of Shiraz, Shiraz, Iran

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Introduction to Port Inventory Optimization

- **- Importance of efficient port operations in global trade and logistics**
- **- Objective: Optimizing inventory level using System Dynamics (SD)**
- **- Scope: Study at Imam Khomeini Port**

Emphasizing the critical role of efficient port operations in global trade and logistics. Efficient port operations are essential for minimizing delays, reducing costs, and improving overall supply chain performance. The study aims to optimize inventory at seaports using the System Dynamics approach, which is suitable for modeling complex systems with feedback loops and dynamic interactions. By focusing on Imam Khomeini Port, the research provides a specific case study that illustrates broader principles.

Problem Statement

- Delays and bottlenecks in port operations
- Impact on cargo and ship dwell times
- Need for a systematic approach to optimize inventory

Delays and bottlenecks in port operations lead to increased cargo and ship dwell times. These delays can result from various factors, including inefficient handling processes, equipment failures, and regulatory bottlenecks.

Prolonged dwell times reduce port efficiency, increase operational costs, and negatively impact the entire supply chain. The slide highlights the necessity for a systematic approach to optimize inventory levels, setting the stage for introducing System Dynamics as the chosen methodology.

Literature Review

System Dynamics	Objects	Title	Authors, Year	No
-	evaluating the factors that influence the dwell time of the shipping containers	Assessing the factors impacting shipping container dwell time: a multi-port optimization study.	Saini, M., & Lerher, T. (2024)	1
✓	The operational efficiency and sustainability of a dry port are evaluated by the developed system of the main parameters.	The introduction to system dynamics approach to operational efficiency and sustainability of dry port's main parameters.	Muravev et al,2019	2
✓	reducing container dwell time and adding capacity at the terminal,	Beyond the seaport: Assessing the inland container transport chain using system dynamics.	Toukan, M., & Chan, H. L. (2018)	3
✓	to predict the performance of the container terminal in terms of the number of unloaded and loaded containers, the turnaround time, and the berth occupancy	Proposing a Model for Forecasting Port Container Terminal Performance; System Dynamics Approach	Haydarpour et al. (2017)	4
✓	to study the maritime transportation system and its integration with multimodal transportation	A review of system dynamics in maritime transportation.	Oztanriseven. Et al (2014)	5
✓	to provide a description of a port as a system of systems	The Port as a System of Systems: a System Dynamics Simulation Approach	Caballini, Sacone, & Siri, 2012	6
✓	To propose a set of archetypical system structures that can explain some commonly observed maritime dynamics	Dynamic Maritime Systems Inquiry: The Driver Approach	Ng and Lam, 2011	7

Dynamic Hypothesis Section 1

- The dynamic hypothesis for optimizing inventory models at seaports, specifically Imam Khomeini Port, revolves around the interplay between cargo dwell time, inventory levels, port efficiency, and resource allocation (equipment and workforce). The core assumption is that reducing cargo dwell time will significantly improve port efficiency and optimize inventory levels, leading to better overall performance of port operations as follows.
- **1- Cargo Dwell Time:**
- - Hypothesis: Longer cargo dwell time increases congestion at the port, leading to inefficient use of resources and reduced overall port performance.
- - Mechanism ⇒ Increased dwell time leads to higher accumulation of cargo in the port's storage areas, which in turn requires more handling and space management efforts.
- **2- Inventory Levels:**
- - Hypothesis: Optimal inventory levels can be achieved by balancing the rate of cargo inflow with the outflow, influenced by efficient handling and reduced dwell times.
- - Mechanism ⇒ When cargo dwell time is reduced, cargo moves faster through the port, lowering the average inventory levels and freeing up resources for incoming shipments.

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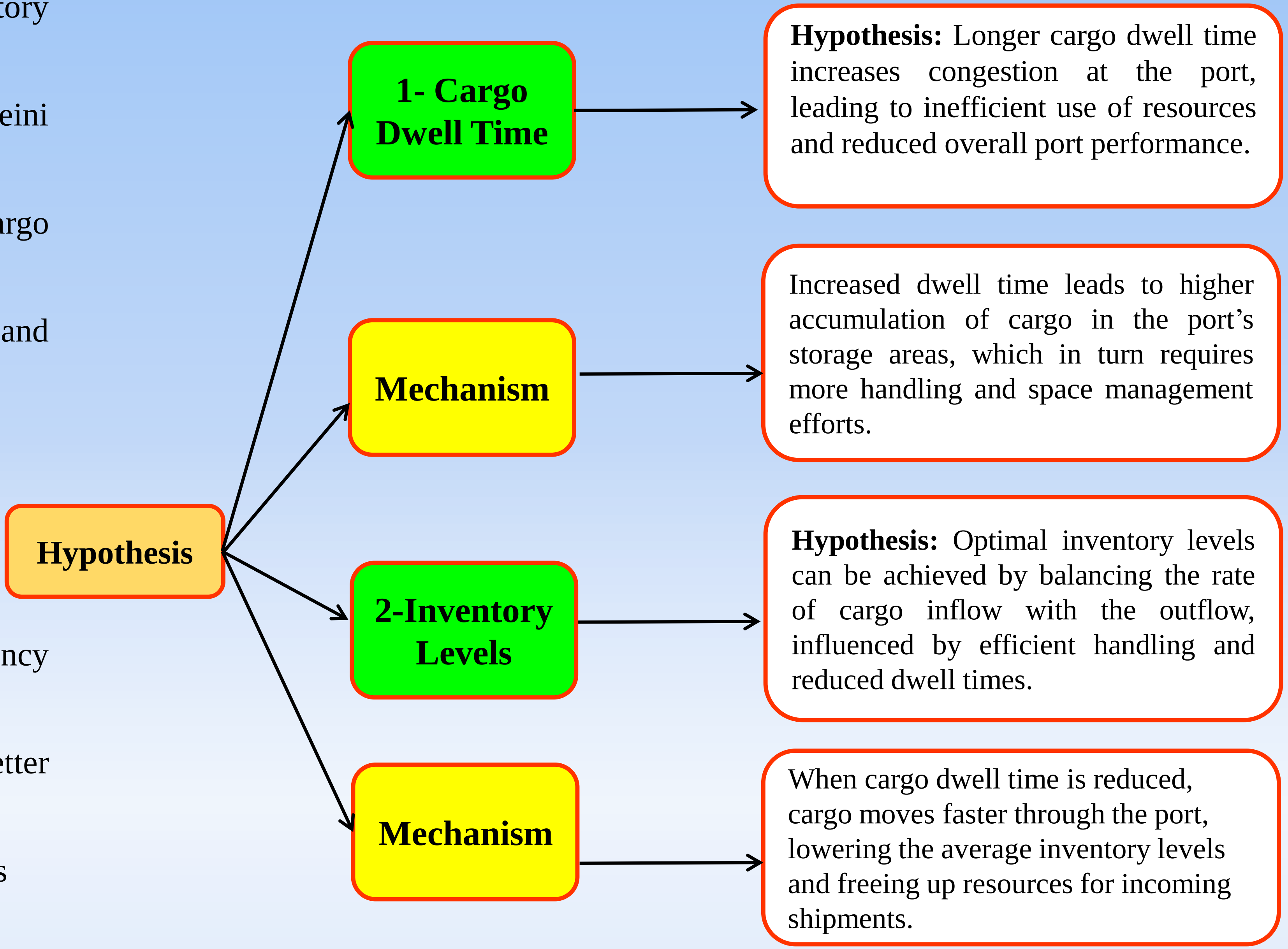

Dynamic Hypothesis Section 2

- **3- Port Efficiency:**
- - Hypothesis: Port efficiency is directly related to the management of cargo dwell time and the optimization of inventory levels.
- - Mechanism → Efficient port operations reduce idle times for ships and equipment, leading to quicker turnaround times and higher throughput.
-

4- Resource Allocation (Equipment and Workforce):

- - Hypothesis: Proper allocation and utilization of resources (handling equipment and workforce) are crucial for managing cargo dwell time and inventory levels.
- - Mechanism: → Sufficient and well-maintained equipment, along with an adequately trained workforce, can handle cargo more efficiently, reducing delays and congestion.

Dynamic Hypothesis Section 2

Hypothesis

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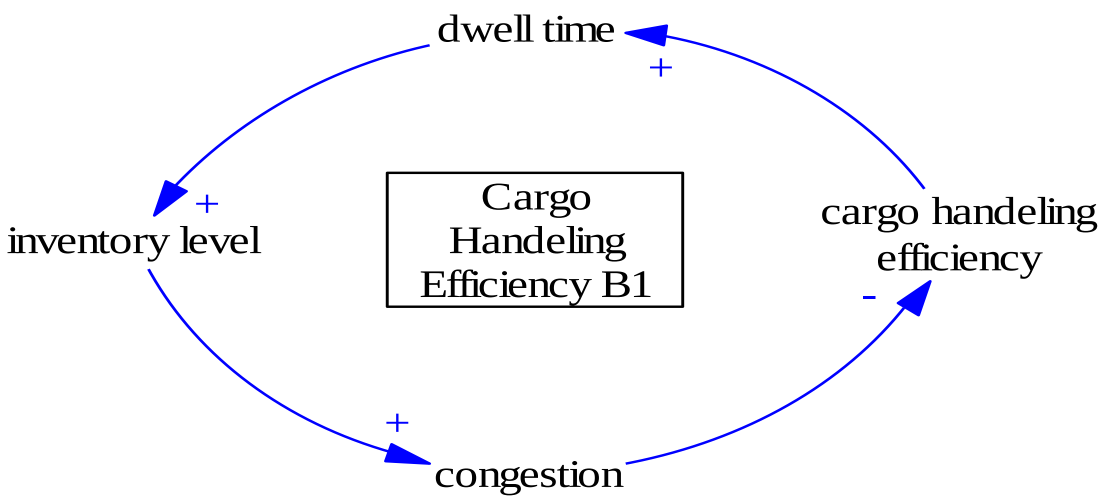
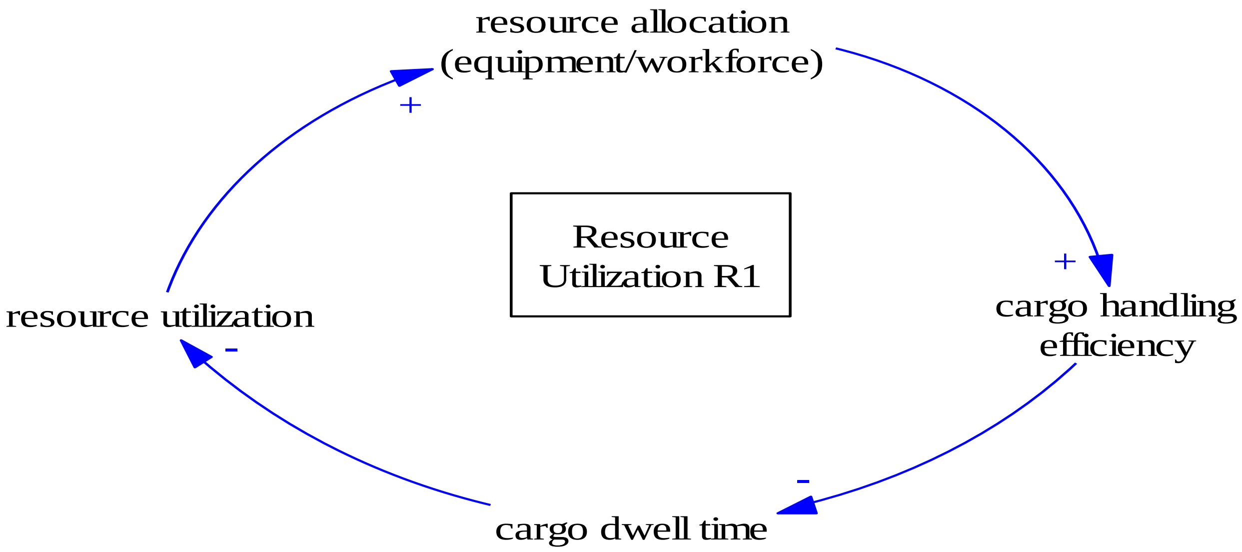
Application of Dynamic Hypothesis in the Model B1

- **1- Balancing Loop B1: Cargo Handling Efficiency**
- - Reduced cargo dwell time -> Lower inventory levels -> Less congestion -> Higher cargo handling efficiency -> Further reduced cargo dwell time



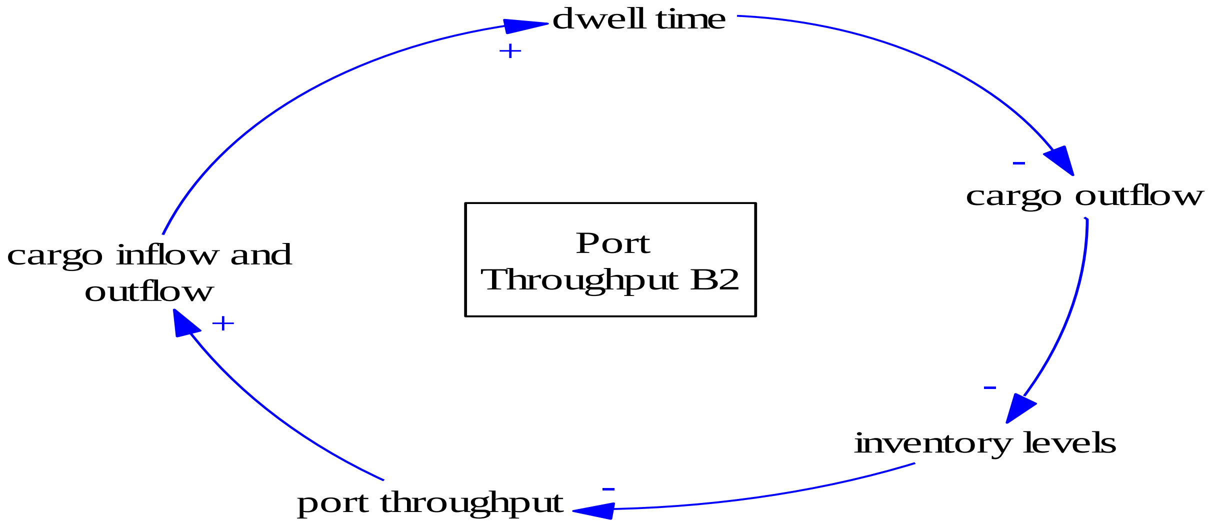
Application of Dynamic Hypothesis in the Model R1

- **2- Reinforcing Loop R1: Resource Utilization**
- - Increased resource allocation (equipment/workforce) -> Improved cargo handling efficiency -> Reduced cargo dwell time -> Better resource utilization -> Justification for increased resource allocation



Application of Dynamic Hypothesis in the Model B2

- 3- Balancing Loop B2: Port Throughput
- - Reduced cargo dwell time -> Faster cargo outflow -> Lower inventory levels -> Increased port throughput -> Decrease Imbalanced cargo inflow and outflow-> Reduced cargo dwell time



Research Questions

- What factors affect port inventory levels?
- How do quay, warehouse, and exit gate impact inventory?
- What policies can control port traffic over time?

- These questions aim to identify the critical factors influencing inventory levels at ports, understand the roles of different port components (quay, warehouse, and exit gate), and explore practical solutions for managing port traffic effectively. By explicitly stating these questions, the presentation provides a clear focus for the audience, helping them understand the specific issues the research aims to address. This approach ensures that the audience can follow the logical progression of the study and see how each part of the presentation connects to these overarching questions.

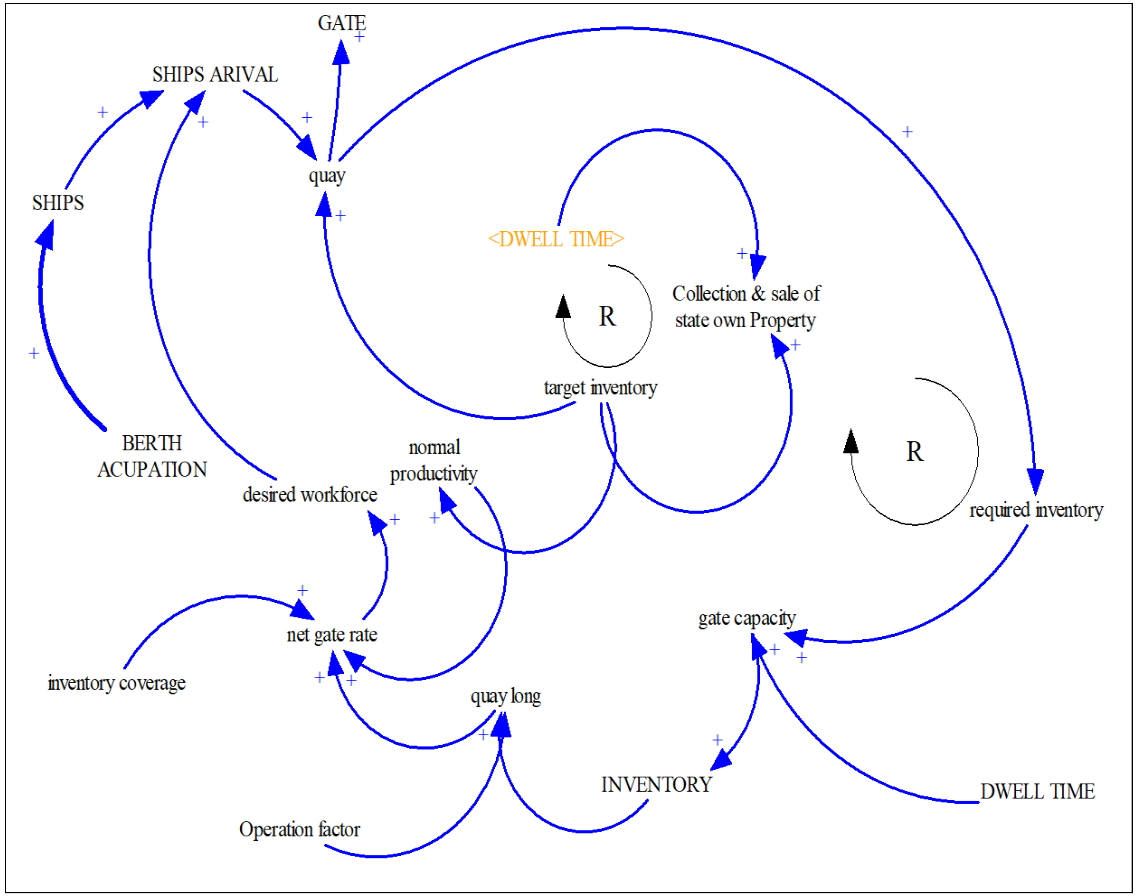
System Dynamics Approach

- Overview of SD methodology
- Relevance of SD for port operations
- Benefits of using SD

- System Dynamics is particularly well-suited for this study because it allows for the modeling of feedback loops, time delays, and dynamic interactions between variables. The slide highlights the benefits of using SD, such as its ability to simulate different scenarios and evaluate the impact of various policies on system performance. This explanation helps the audience understand why SD was chosen as the methodology for this study and addresses reviewers' comments on the need to justify the choice of SD. By explaining the core principles of SD, the slide lays the groundwork for understanding the subsequent modeling work.

Conceptual Model

-Introduction to causal loop diagrams (CLD)
- Key variables and their interactions
- Figure: CLD for cargo handling and inventory

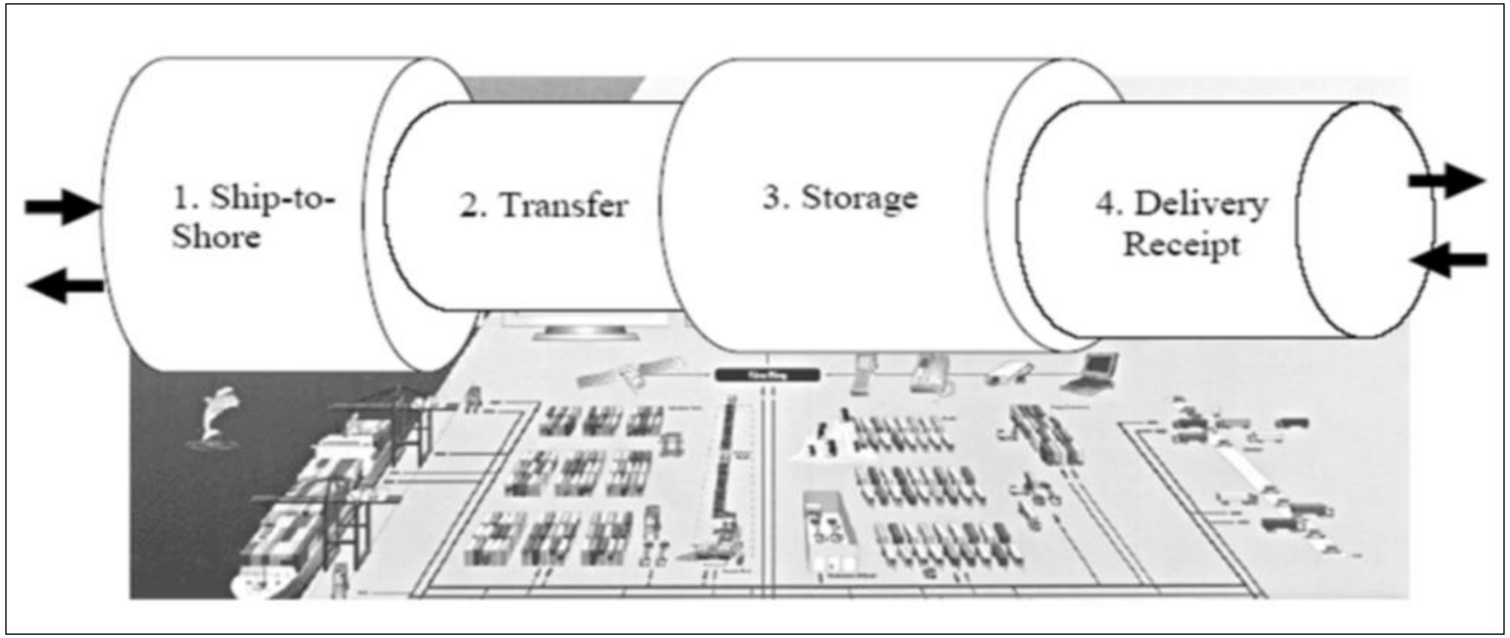


Conceptual Model

- The previous slide introduces the conceptual model using causal loop diagrams (CLD). CLDs are a tool used in System Dynamics to visualize the relationships between key variables and the feedback loops that influence system behavior. The slide explains how CLDs help identify and understand the dynamic interactions between variables in port operations, such as cargo dwell time, inventory levels, and port efficiency. This figure provides a visual representation of the CLD for cargo handling and inventory, illustrating the key variables and their interactions. By clearly presenting the conceptual model, this slide addresses reviewers' comments on the need to explain how the model was developed and the rationale behind it

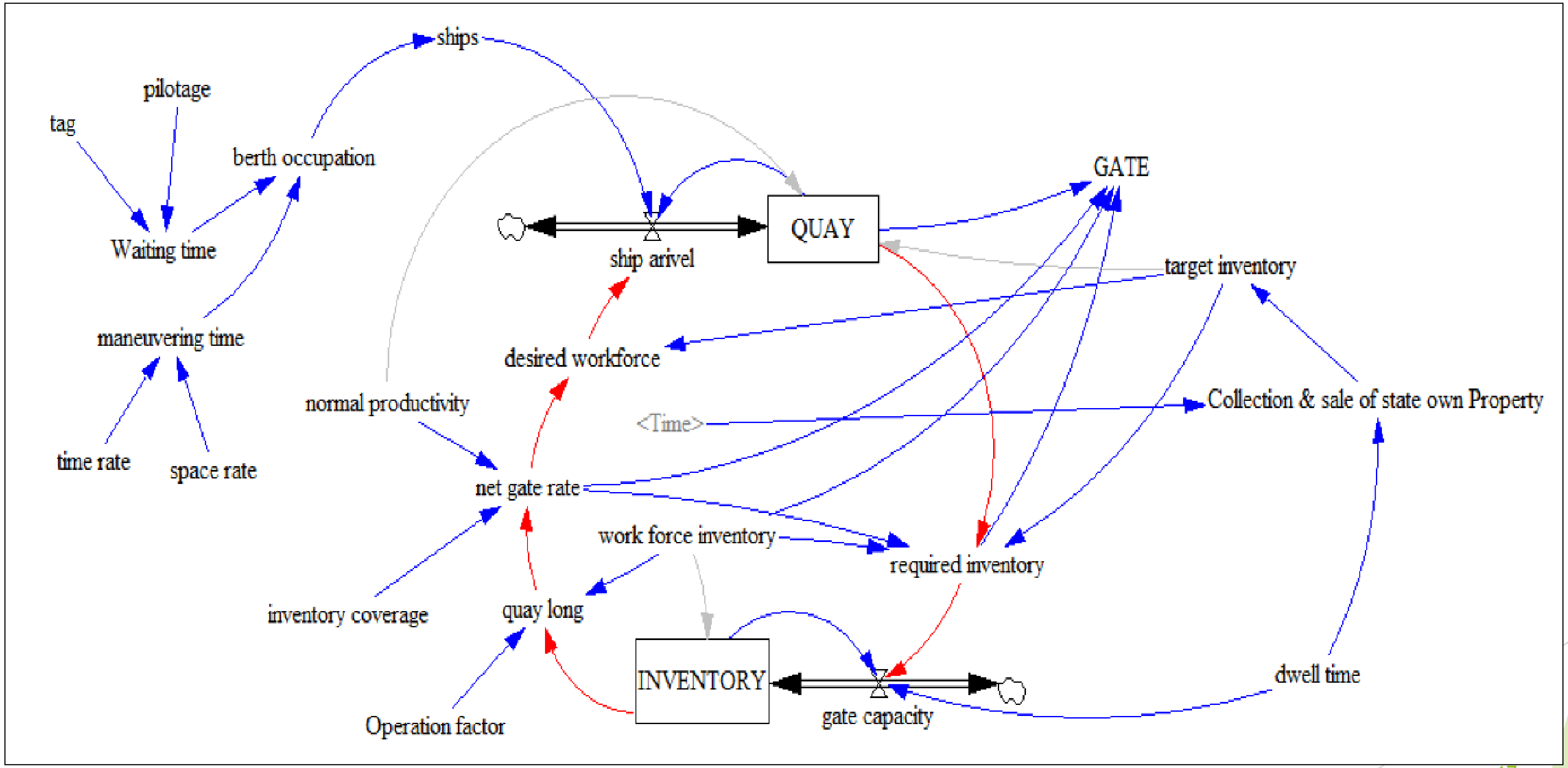
Stock and Flow Diagram

- Explanation of stock and flow diagrams
- Interaction between system variables
- Figure: Stock-flow diagram of port operation



A Schematic view of entering cargo to port

Stock and Flow Diagram



Stock and Flow Diagram

- This last slide delves into the stock and flow diagram, a core component of System Dynamics models that illustrates the accumulation and flow of resources in a system.

- Stock variables represent the quantities of resources, such as inventory levels, while flow variables represent the rates of change, such as the rate of cargo arrival and departure.

- The slide explains how the stock and flow diagram helps model the interactions between various system variables and track changes over time. The last figure provides a visual representation of the stock-flow diagram for port operations, showing how different factors influence inventory levels.

Methodology Overview

- Steps in the modeling process
- Conceptualization, formulation, validation
- Use of Vensim DSS software

- Data Collection
  - 1- Sources of data
  - 2- Methods of data collection
  - 3- Importance of accurate data
- Model Formulation
  - 1- Developing the model equations
  - 2- Key variables and their acronyms
  - 3- Table of variables

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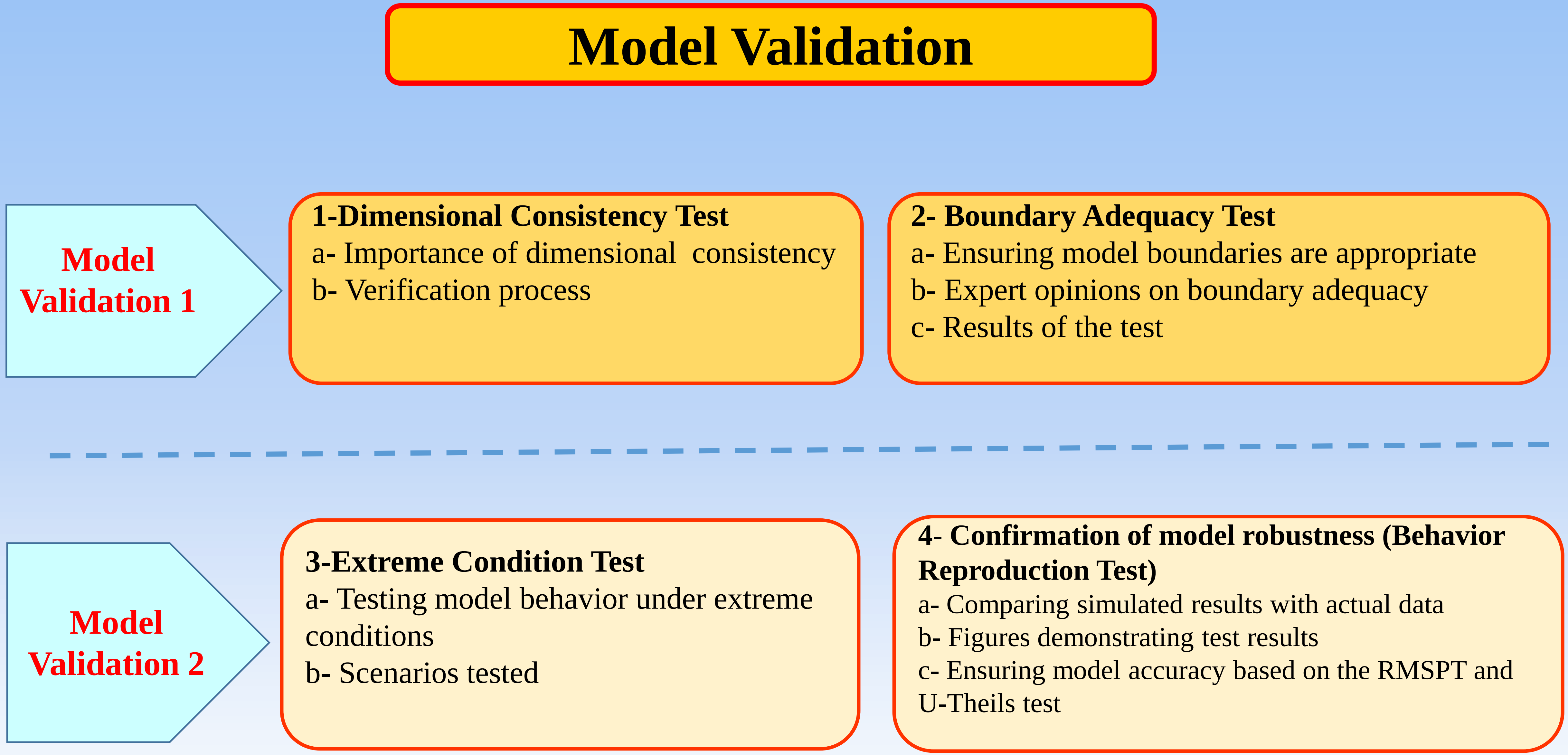
List of variables based on acronyms

Variable Name	Abbreviation	Variable Name	Abbreviation
Maneuvering Time	MT	Target Inventory	TIN
Waiting Time	WT	Required Inventory	RIN
Berth Occupation	BO	Inventory	IN
Ship arrival	SA	Dwell Time	DT
Quay	Q	Work Force Inventory	WFIN
Gate	G	Desired workforce	DW
Collection & Sale	COLL	Normal Productivity	NP
Quay long	QL	Gate Capacity	GC
Net gate Rate	NGR	Space Rate	ST
Time Rate	TR	TUG	TUG
Pilotage	PIL		

List of Model Equations

variable	Equations
Maneuvering Time	MT=ST*TR
Waiting Time	WT=PIL*TUG
Berth Occupation	BO=MT*WT
Ship arrival	SA=100+(DW-Q)/S
G	G= Q*RIN*NGR/WFI
Required Inventory	ZIDZ(target inventory, QUAY*net gate rate) * work force inventory
Quay long	Operation factor*(INVENTORY/work force inventory)
Net gate Rate	normal productivity*inventory coverage*(quay long)
Desired workforce	ZIDZ(target inventory, net gate rate)


Model Validation
Model Validation 1
1-Dimensional Consistency Test
a- Importance of dimensional consistency
b- Verification process
2- Boundary Adequacy Test
a- Ensuring model boundaries are appropriate
b- Expert opinions on boundary adequacy
c- Results of the test
Model Validation 2
3-Extreme Condition Test
a- Testing model behavior under extreme conditions
b- Scenarios tested
4- Confirmation of model robustness (Behavior Reproduction Test)
a- Comparing simulated results with actual data
b- Figures demonstrating test results
c- Ensuring model accuracy based on the RMSPT and U-Theils test

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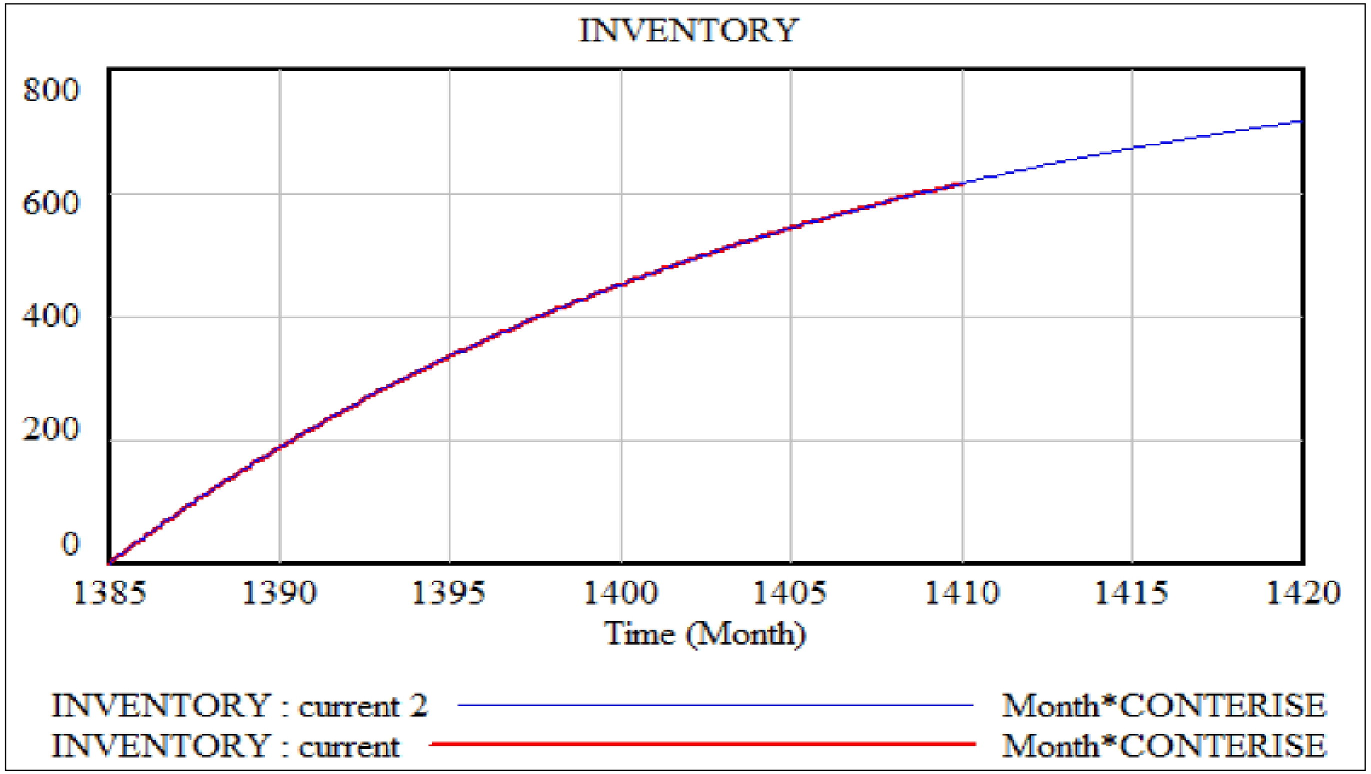
Time Boundary Efficiency

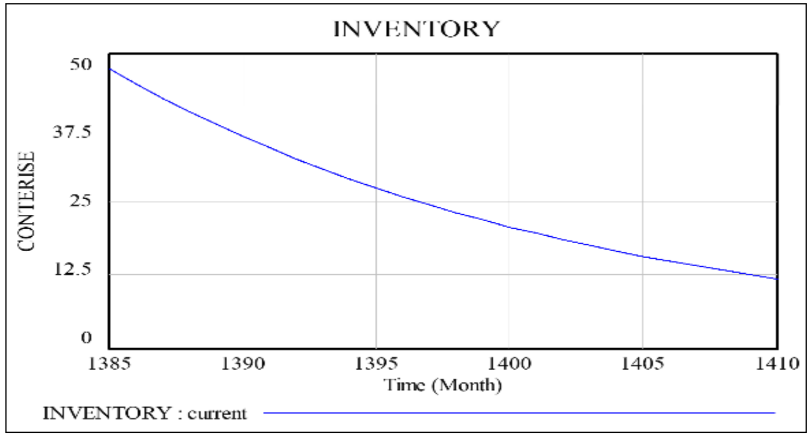
Indicates whether the trend of the key variables of the pattern is changed using the opening interval. In this regard, the inventory level does not change despite the increase in timeframe from 1410 to 1420

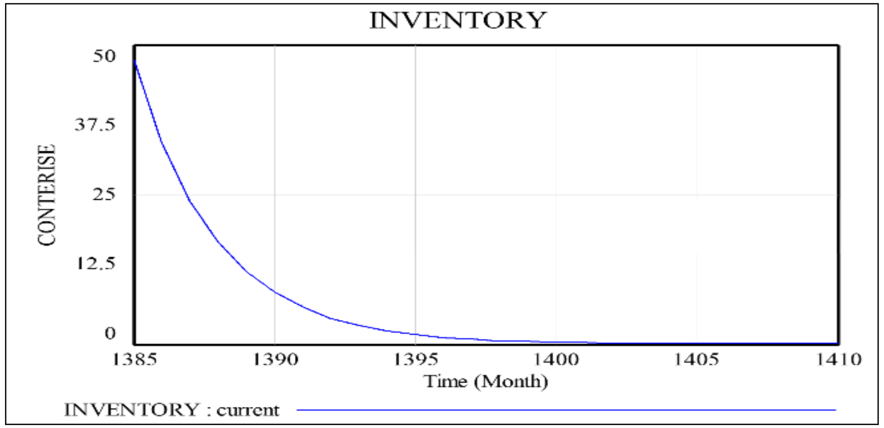
Time boundary Efficiency test



Extreme Condition Test

The model structure and output should be plausible for any extreme and unlikely combination of levels of factors in the system. For example, if in-process inventories are zero, production output should be zero (Sargent, 2010). Extreme condition tests were carried out in this paper assuming zero delivery of goods to the berth and a constant rate of dwell time. As shown in Figure, if the maneuvering equipment (Tug) or manpower is idle, the inventory level is zero (right figure). Also, if the cargo deposition in the warehouse is zero, the inventory level decreases and moves downwards (as shown in the left-hand figure), confirming the assumptions of this test.



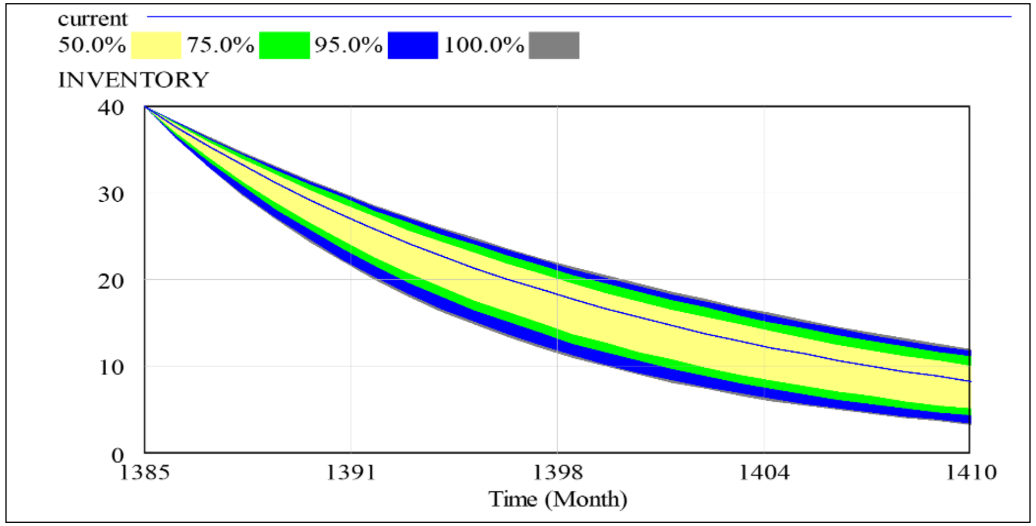


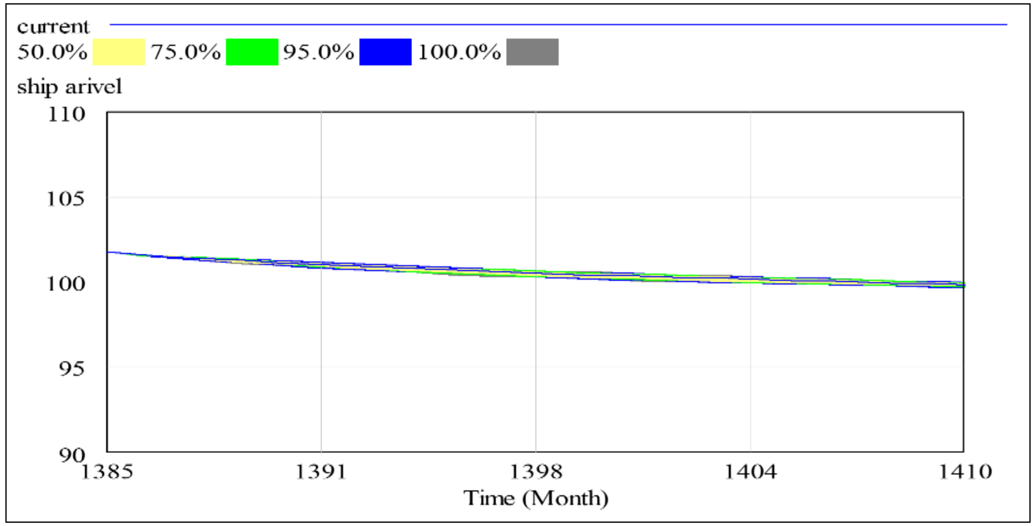
Sensitivity Analysis

- Impact of varying key parameters
- Figures illustrating sensitivity results
- Importance of sensitivity analysis

- After verifying the structure and behavior of the model, the researcher analyzes the policies, or in other words, scenarios, to enhance the performance of the design model and the results obtained from the implementation of these policies (Mousavi Haghighi & Tajik, 2014).
- In this section, the sensitivity of inventory and the number of inbound vessels will be measured relative to the time of deposition of goods. For this purpose, the cargo dwell time is changed by 50% and the effect on the variables is examined. As shown in figure 11, the effect of this change on the stock is very high.

Sensitivity Analysis Results





Error calculation tests

A. Root Mean Squares Percentage Error
B- Identify the Root of the Error

$$RMSPE = \sqrt{\frac{1}{\theta}\sum_{i=1}^{\theta}\left(\frac{y_{T+i}^{s} - y_{T+i}^{a}}{y_{T+i}^{a}}\right)^2} * 100$$

$$UT = \sqrt{\frac{\frac{1}{\theta}\sum_{i=1}^{\theta}(y_{T+i}^{s} - y_{T+i}^{a})^2}{\frac{1}{\theta}\sum_{i=1}^{\theta}(y_{T+i}^{s})^2 + \frac{1}{\theta}\sum_{i=1}^{\theta}(y_{T+i}^{a})^2}}$$

$$U^m + U^s + U^c = 1$$

$$U^m = (\bar{Y}^s - \bar{Y}^a)^2 / [\frac{1}{\theta}\sum_{i=1}^{\theta}(Y_{T+i}^{s} - Y_{T+i}^{a})^2]$$

$$U^s = (SDS - SDA)^2 / [\frac{1}{\theta}\sum_{i=1}^{\theta}(Y_{T+i}^{s} - Y_{T+i}^{a})^2]$$

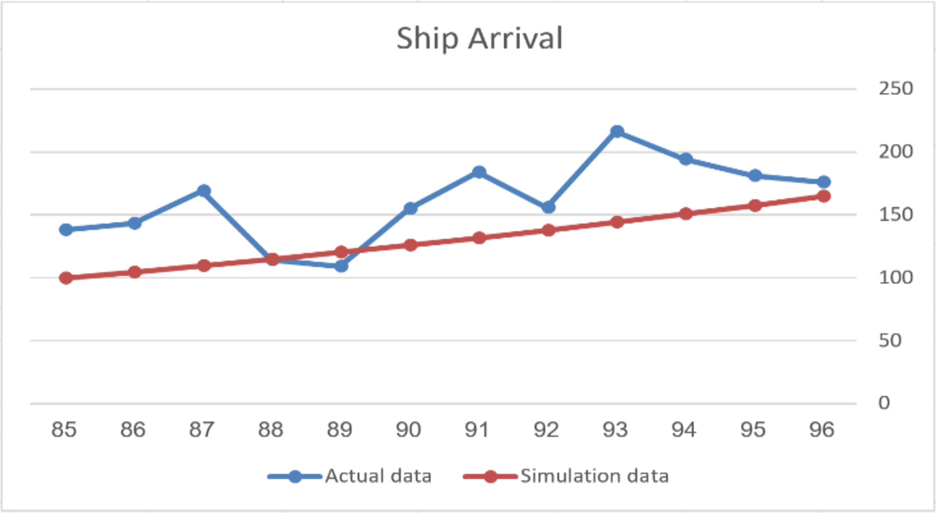
$$U^c = [2*(1-r)*(SDS * SDA)] / [\frac{1}{\theta}\sum_{i=1}^{\theta}(Y_{T+i}^{s} - Y_{T+i}^{a})^2]$$

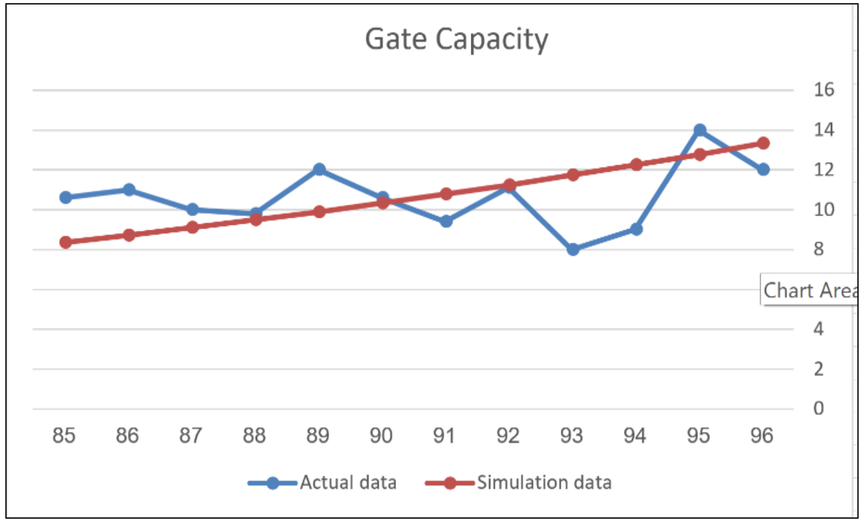
Model Validation 2

Results of statistical tests of model validation

Gate Capacity	Ship arrival	Test
0.2077	0.2232	RMSPE
0.1278	0.1859	UT
0.0009	0.6621	U^m
0.0276	0.0862	U^s
0.9715	0.2517	U^c
1	1	$U^m + U^s + U^c$

Behavior Reproduction Test





Simulation Scenarios

- Description of different scenarios tested
- Importance of scenario analysis
- Figures showing scenario outcomes

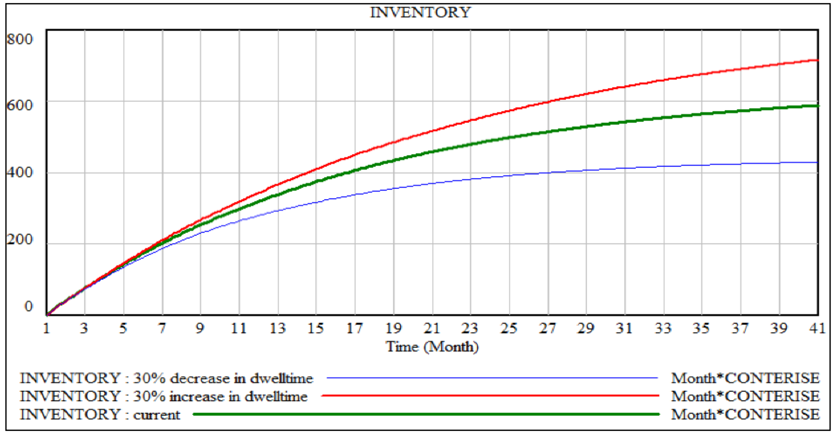
- Scenario analysis is a powerful tool in System Dynamics for exploring the impact of different policies and conditions on system behavior. The slide explains the scenarios tested, such as changes in cargo dwell time, workforce levels, and storage capacity. Figures are included to show the outcomes of these scenarios, providing visual evidence of the model's insights. By detailing these scenarios, the slide addresses reviewers' comments on the need for a thorough analysis of different policy interventions and their potential impacts. This approach helps the audience understand the practical implications of the study's findings.

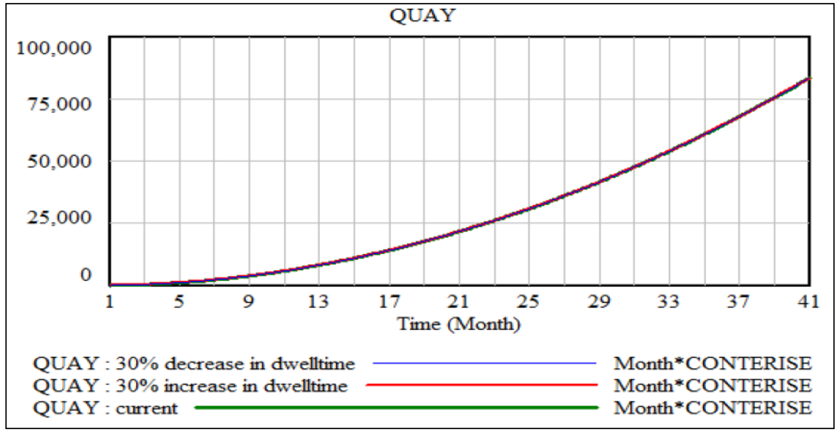
Scenarios

- Scenario 1: Dwell Time Reduction
- a- Effect of reducing cargo dwell time
- b- Figures showing inventory and quay behavior
- c- Policy implications

- Scenario 2: Combined Effect
- a- Combined effect of reducing dwell time and increasing workforce
- b- Figures showing inventory behavior
- c- Analysis of results

Scenario 1: The effect of reducing the cargo dwell time on stock inventory and labor requirements





Scenario 2: Changes in the cargo dwell time and work force simultaneously

Discussion of Results

- Key findings from simulations
- Practical implications for port management
- Recommendations

- The slide summarizes the main insights gained from the scenarios and sensitivity analyses, highlighting the most significant factors affecting port inventory levels.
- It provides recommendations for port managers based on these findings, such as implementing policies to reduce dwell time and optimizing workforce levels.

Conclusion

- Summary of study contributions
- Key takeaways
- Quantitative Results
- Future research directions

- **Summary of study contributions:**
- This study effectively applies a system dynamics (SD) approach to optimize inventory management at seaports, with a focus on Imam Khomeini Port in Iran. The research underscores the significant impact of reducing cargo dwell time on overall port performance and inventory fluctuations. By incorporating both internal and external factors, the SD model provides a comprehensive framework for understanding the dynamic interactions between various port operations variables.
- **Key takeaways include:**
- a- Practical Implications: The findings offer actionable insights for port authorities and operators to enhance decision-making processes and improve operational efficiency through better inventory management and reduction of cargo dwell time.
- b- Holistic Approach: The model integrates multiple variables, including workforce, equipment, and infrastructure, demonstrating the interconnectedness and complexity of port operations.
- c- Sensitivity Analysis: The study highlights the sensitivity of warehouse operations to adjustments in cargo dwell time, suggesting that even minor improvements can lead to substantial benefits.
- d- Scenario Analysis: Further development of scenario analyses, considering various policy interventions, would enhance the model's robustness and applicability in real-world settings.

Conclusion

- **Quantitative Results:**
- a- Reduction in Cargo Dwell Time: The study shows that a 30% reduction in cargo dwell time leads to a significant improvement in inventory fluctuations compared to a corresponding increase in workforce.
- b- Sensitivity of Warehouse Traffic: Even low adjustments in dwell time management greatly impact warehouse operations, while having a lesser effect on workforce efficiency.
- c- Impact on Inventory Models: The model's simulations indicate that optimizing cargo dwell time can substantially reduce delays and interruptions, leading to a more streamlined and efficient inventory management system.

Conclusion
Future Research Directions Part 1

- 1- Integration of External Factors: Future research should incorporate external factors such as global trade fluctuations, regulatory changes, and geopolitical influences to provide a more comprehensive understanding of their impact on port inventory management.

- 2- Enhanced Model Validation: Further rigorous validation of the SD model using historical data, statistical methods, and empirical observations will enhance its reliability and applicability. This could involve collaboration with other ports and research institutions to gather a broader dataset.

- 3- Development of Advanced Scenarios: Expanding scenario analysis by integrating various policy interventions, such as process streamlining and workforce training, will provide deeper insights into the potential outcomes and enhance decision-making strategies.

Conclusion
Future Research Directions Part 2

- 4- Technological Integration: Investigating the role of advanced technologies, such as artificial intelligence and blockchain, in optimizing inventory management and reducing dwell time could offer new avenues for improving port operations.

- 5- Stakeholder Engagement: Engaging more stakeholders, including port authorities, logistics companies, and government agencies, in the development and validation of the SD model will ensure its practical relevance and facilitate the implementation of the proposed strategies.

- 6- Comparative Studies: Conducting comparative studies across different ports globally to identify best practices and benchmarks can help in refining the model and making it adaptable to various operational contexts.

Thank you for your consideration and patience.