A Methodology for Evaluating Decision Support Systems in the realm of Steel Ladle Logistics

by

Akhil Raja Keshetti

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Department of Computer Science
Faculty of Electrical Engineering,
Mathematics and Computer Science,
University of Twente,
Enschede, Overijssel, The Netherlands

UNIVERSITY OF TWENTE.

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FACULTY OF ELECTRICAL ENGINEERING, MATHEMATICS & COMPUTER SCIENCE

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Author

Akhil Raja Keshetti

Data Science & Business
Faculty of Electrical Engineering, Mathematics & Computer Science (EEMCS)
University of Twente

University Supervisors

Hao Chen

Industrial Engineering and Business Information Systems
Faculty of Behavioural, Management and Social Sciences (BMS)
University of Twente

João R. Moreira

Semantics, Cybersecurity and Services
Electrical Engineering, Mathematics & Computer Science (EEMCS)
University of Twente

Marcos R. Machado

Industrial Engineering and Business Information Systems
Faculty of Behavioural, Management and Social Sciences (BMS)
University of Twente

Company Supervisors

Victor S. P. Ruela

Doctoral Candidate
Ceramics Research Centre, Tata Steel Ijmuiden
Institute for Energy Systems and Thermodynamics, TU Wien

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ABSTRACT

The research to make the manufacturing processes energy efficient and sustainable is imperative. Given the significant production demand and energy consumption, the iron and steel industry plays a predominant role in this endeavor. The adoption of Industry 4.0 by the steel industry is essential for enhancing manufacturing processes' energy efficiency and environmental sustainability. Advanced Analytics emerged as the core pillar of Industry 4.0 owing to its capabilities of digitizing collection, storing, and various methods of analyzing data, offering invaluable insights for fulfilling sustainability goals. The steel-making industry can implement such analytics to make the production process energy efficient, given the availability of necessary historical data. In the steel-making process, steel ladle logistics is a prominent operation, that can be made energy-efficient using Advanced Analytics. Steel Ladle Logistics refers to the management, monitoring and transportation of ladles used in steel-making process. The scientific landscape has State-of-the-Art decision support systems built using mathematical models to generate optimal ladle logistics schedules. But the practical applicability of these solution methods remained uncertain, due to the absence of robust methodologies in literature that can be adopted to validate the usability in real-time. As a result, the primary motivation of the study is to fill the gap in literature by proposing an validation methodology by adopting simulation techniques. By integrating a simulation model (that replicates the real world dynamics of steel ladle logistics) along side the optimization model, feasibility to respect the system constraints and comparative analysis on the system performance was evaluated. It was aimed to analyse the feasibility of carrying out model generated decisions without conflicts and respecting minimum tapping temperature constraint in real time. The methodology suggests to identify a set of sustainability indicators that can be adopted to realize the effect of optimization model results on system performance. In this research study, CO_2 emissions and steel temperature losses are chosen and analysed as sustainability indicators of steel ladle logistics.

Keywords: Steel Ladle Logistics ; Scheduling ; Optimization Models; Discrete Event Simulation; Feasibility Analysis ; Sustainability Analysis

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ABBREVIATIONS

BF-BOF Blast Furnace-Basic Oxygen Furnace.

BOF Basic Oxygen Furnace.

CGM Slab Casters.

CT Cross Transport.

CV Converter.

DES Discrete Event Simulation.

DSP Direct Sheet Plant.

EAF Electric Arc Furnace.

EOL End-of-the-Life.

GK Casting Crane.

KS Tilting Stand.

LF Ladle Furnace.

MIP Mixed Integer Programming.

OSF2 Oxygen Steel Factory 2.

PO Pan Oven/Ladle Furnace(EN).

ROM Reduced Order Model.

SDG Sustainable Development goals.

SLR Systematic Literature Review.

SS Stirring Station.

TSNL Tata Steel Nederland.

UDF User Defined Function.

UNSDG United Nations Sustainable Development Goals.

VPB Vacuum Degasser.

WHS Warm Houd Stand/Reheating Stand(EN).

1

INTRODUCTION

The steel and iron industry emits significant CO_2 and accounts for up to 8% of global energy demand [44]. According to the World Steel Association, demand for steel production is rising and is expected to grow by 1.4% in 2024 [93]. To satisfy the growing demand of steel, it's vital to adopt energy-efficient practices, while maintaining consistent production quality, essentially producing more steel with the less or equal amount of energy consumption as now. Researchers emphasise that "to reduce the use of fossil fuels and achieve net-zero emissions by 2050, hydrogen can be used as replacement for fuels in high CO_2 emitting processes" [21].

Steelmakers worldwide increasingly considering the adoption of hydrogen-operated DRI furnaces against blast furnaces to substantially reduce the CO_2 emissions [77]. But there's still untapped potential at downstream processes, especially during steel-making and casting. To enhance sustainability, optimization of steel ladle logistics is significant and inevitable [72]. This is because of the significant energy consumption associated with the ladle operations in steel plants. In the following subsections steel-making process, steel ladle logistics, and the requirement to make the steel ladle logistics energy efficient are explained.

1.1. STEEL-MAKING PROCESS

Steel-making is one of the largest energy-consuming industries [44] due to various operations involved with the production process. In accordance with the production technique, steel-making is most frequently categorized into two routes: The Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and the Electric Arc Furnace (EAF) route [24]. Blast furnace produces iron from iron ore, which will be further converted into steel in a basic oxygen converter with scrap additions. Whereas in the EAF route, steel will be produced mainly from scrap collected for recycling. However, it also has the potential for smelting solidified or sponge iron [24]. EAF has relatively lower emissions when compared to BF-BOF, but can only produce limited steel grades [24]. The focus of the current research context addresses the BF-BOF route.

According to Worldsteel Association [94], the generic BF-BOF steel-making process commences with the procurement of raw materials such as iron ore, limestone, and charcoal, sourced from diverse geographical locations based on the desired grade of the final product. Iron ore together with limestone and other minerals, will be transported to the sintering plant, where they are amalgamated at high temperatures to form ***'sinters'*** (small, crushed nodules), that are to be used in the blast furnace. Concurrently, the acquired charcoal will be processed into fuel for blast furnaces in coke ovens, by heating them to separate coal gas and coal water to produce ***'coke'***, which helps in smelting sinter's in blast furnace.

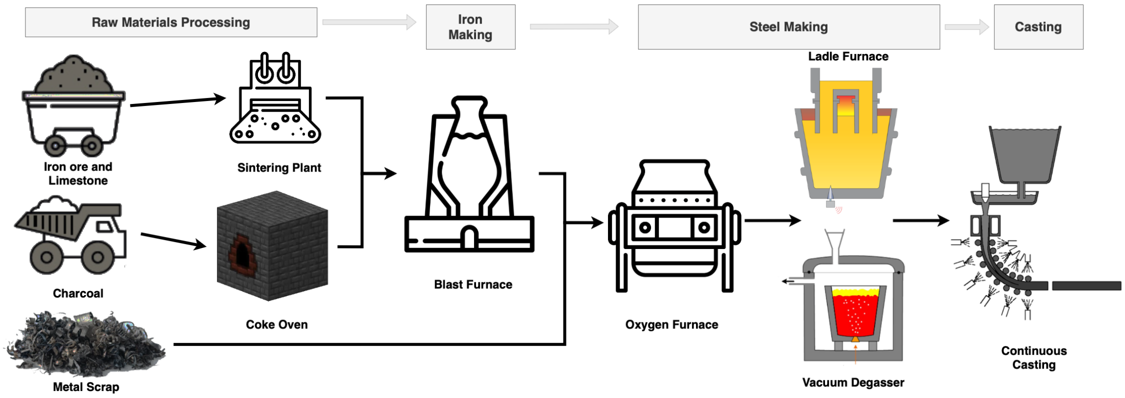

Figure 1.1: Steel-Making Process

A subsequent process would be to convert iron oxides to molten iron. This process will be accomplished in blast furnaces. The blast furnace is a brick-lined stack, where the sinters from the sintering plant will be converted into hot metal using the coke gas at a higher temperature and pressure from the coke oven. The carbon-rich hot metal from the blast furnace needs to undergo further production processes to form into steel composition. This will be accomplished in Basic Oxygen Furnace (BOF). In BOF plants, hot metal (with 4% to 5% carbon content) is oxidized utilizing additional metal scrap by an exothermic oxidation technique which reduces it into steel with below 2% carbon composition.

Following the BOF plant treatments, Ladle Furnace (LF) will be used for the secondary refinement of molten steel. The ladle furnace acts as a purifier of molten steel and, a metallurgical operator reactor for secondary treatments. The purified molten steel undergoes further treatments in a Vacuum Degasser (VPB) where it separates the dissolved gases from molten steel by combining lower internal pressure with the liquid and removes them using vacuum pumps. Subsequently, the molten steel will be casted into desired shapes such as slabs, sheets, rods etc., completing the cycle of steel-making process.

1.2. STEEL LADLES

In order to transport the raw materials, and by-products between each stage of the steel-making process, different transporting equipment will be required. The general equipment being used in the process are:

- **Torpedo Car:** Torpedo car will be transporting the hot metal produced in the blast furnace to the converters for steel making.
- **Hot Metal Ladles:** The molten steel transported from the blast furnace in torpedo cars will be dumped into hot metal ladles. These ladles will take care of transporting hot metal to BOF for primary refining.
- **Steel Ladles:** The product of BOF would be molten steel with the desired chemical composition. Now it is the responsibility of steel ladles to transport the molten steel from the the primary refining installations to undergo secondary metallurgy and then for continuous casting.

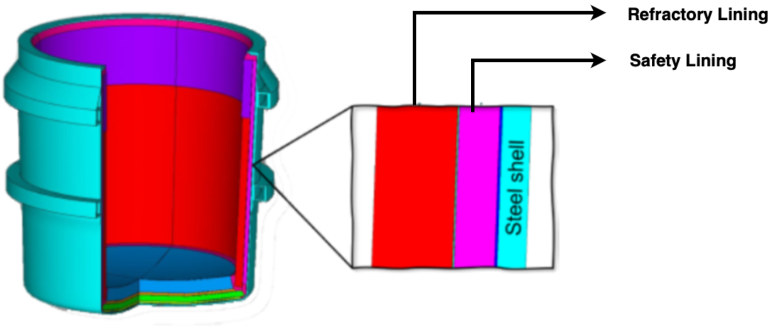

Figure 1.2: Steel Ladle Cross-sectional View [85]

In each of the transporting equipment, special arrangements will be made by the steel plant for withstanding high-temperature tapping and holding the temperature of hot metal or molten steel. Refractory linings are required to accomplish this task as depicted in Figure 1.2. In the context of steel-making, refractory lining relates to a heat-resistant layer that protects the inner surface of transportation equipment from high temperature and the corrosive effects of hot metal or molten steel. In detailed explanation of refractories, their importance in improving the energy efficiency of steel-making process is described in [87].

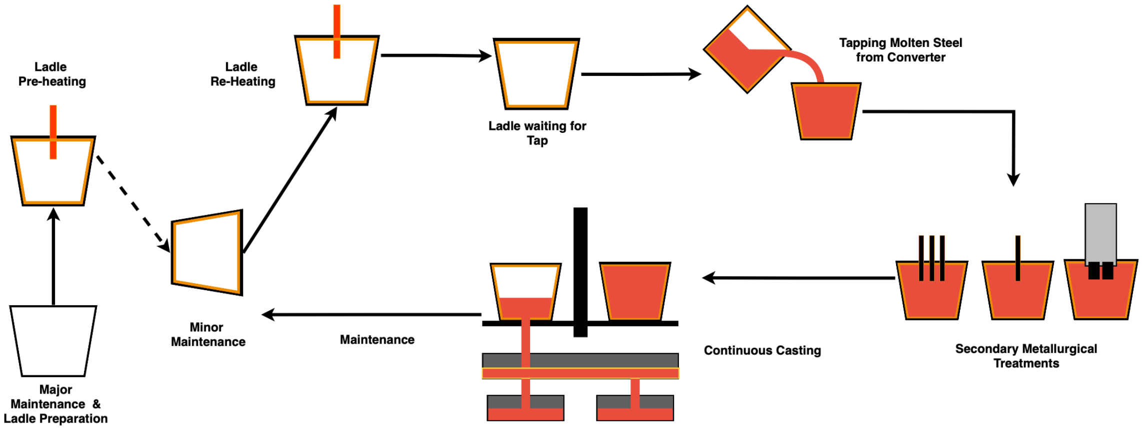

Figure 1.3: Steel-Making Operational Cycle of Steel Ladles

Steel ladles have an invaluable importance in the steel-making process owing to the operations it accomplishes. As we delve deeper into the steel-making processes (as described in Figure 1.1), steel ladles carry out undergoes numerous operations to complete an single operational cycle. They are:

- **Tapping Molten Steel:** Researchers and practitioners across the steel-making industries possess distinct opinions on starting point of steel-making process. In the current study, it was assumed that the process starts from tapping molten metal into steel ladles. Following the conversion of hot metal into molten steel (as described in 1.1) by oxidation process at BOF, it would be ready for secondary metallurgical treatments. So, the molten steel will be tapped into a steel ladles at the BOF.

- **Secondary Metallurgical Treatment:** This phase, also addressed as *"Secondary steel-making treatments"* typically carries out three operations: Stirring, Ladle Furnace and Vacuum Degassing. The steel ladles holding molten steel also acts as a reactor for metallurgical treatments. The refining operations in ladle furnaces typically involve deoxidation, alloying, desulphurization, etc. Stirring molten steel is carried out to enhance the kinetics of refinement, subsequently separating non-metallic inclusions as slag, which can continue for the entire ladle metallurgical cycle. Along with stirring plugs or plunges, argon gas in connection to the ladle furnace will be used for attaining a homogeneous composition in molten steel. A vacuum degasser will be adopted to eliminate dissolved gases such as H_2S, Nitrogen, and corrosive oxygen which lead to defects such as cracks in the steel casts[88].

- **Continuous Casting:** As the molten steel reaches desired chemical composition and thermal state during secondary metallurgy treatments, it will be transported to casting machines. Now the molten steel will be cast into slabs or sheets and further processed into required end products.

- **Maintenance:** After each cycle of steel-making, steel ladles are deemed to undergo either minor or major maintenance. Minor Maintenance addresses removal of solidified slag on the walls of refractory lining, adding filler sand, replacing sliding plates. Operators would make sure to pour down remaining liquid slag in the ladle at dedicated locations, before moving it to minor maintenance. Where as, the Major Maintenance addresses replacement of refractory lining, when it reaches the end of life conditions.

- **Ladle Pre-heating:** Following relining through major maintenance, the ladle needs to undergo pre-heating to prevent damage to the refractory lining due to thermal shocks during the tapping of molten metal. This phase can span up to 40 hours to attain a refractory temperature up to 1000 °C [22].

- **Ladle Re-Heating:** In order to make the ladle suitable for tapping molten steel, the ladle refractory lining should be at a certain thermal state based on production requirements. So, the ladle will be re-heated to reach the desired thermal state, if necessary. The duration of the re-heating phase is contingent on two factors: the temperature of the ladle refractory prior to re-heating and the desired temperature post-re-heating.

- **Waiting:** After the ladle reaches the desired thermal state, it will be transported to the converter location for tapping the molten steel. Depending upon the availability of transport cars and cranes, the ladle can wait at the reheating station until they become available or transported to the converter station and wait on the transport car until the converter starts tapping the molten steel.

As observed in the series of operations accomplished by the steel ladles, they remain in contact with the heat most of the time, except during the maintenance and waiting phase before reheating for the next production charge. In order to receive the molten steel in each tapping operation, the steel ladle needs to satisfy certain thermal conditions. This is because the ladle refractories must endure the thermal shocks and high temperatures associated with molten steel. Adequate thermal conditions would also prevent temperature losses of molten steel and minimize heat conduction from molten steel to the refractory linings. Failing to maintain the ladle at the intended thermal stage results in higher refractory lining wear and raises safety concerns [72, 87]. In order to prevent such adverse conditions, adequate reheating of the ladle is required before dispatching it to charge. As a result, it emphasizes that it is important to research in the context of steel ladle logistics to improve the energy efficiency of steel-making process.

1.3. RESEARCH MOTIVATION AND PROBLEM DEFINITION

Research regarding energy efficiency in steel ladle logistics is limited to the heating and waiting times of the ladles [72]. However, it does not provide a complete solution for ladle energy efficiency as it overlooks the ladle's thermal balance. This oversight raises safety concerns due to the adverse effects of the decrease in refractory linings thickness, which is detailed in [72, 87].

According to Tesselaar et al. [87], several factors affect the balance between steel quality and energy efficiency in steel ladle logistics: safety, availability, reliability, heat size, product quality, and total refractory cost. The authors emphasize that the ladle value can be increased in operations by better understanding the behaviour of refractory material and its heat interaction during the steelmaking process. Ruela et al. [72] showed that an inefficient ladle logistics schedule can lead to production and quality issues, unnecessary energy loss, and increase in wear rate, ultimately resulting in higher refractory consumption. So, by analyzing the relation between the thermal behavior of ladles and the wear rate of refractories, steel plants can enhance the availability, energy efficiency and sustainability of ladles as addressed by Ruela et al. [72].

The researchers have made efforts in understanding energy intensive operations in connection to steel ladles and adopted the insights to optimize steel ladle logistics [87]. In the process of addressing the issue, Ruela et al. [72] developed an optimization model that investigates the energy efficiency of ladle deployment decisions considering the thermal state of the ladles.

It implies that the optimization model calculates an optimal ladle schedule using theoretical ladle energy balance equations. However, these schedules are ideal and may not represent real situations in the plant.

In general, optimization models are developed under certain theoretical assumptions and ideal conditions. One of the prominent simplifications observed was to assume stochastic process parameters as deterministic. It means that the models have limited representation of the real-world scenarios. The schedules or decisions generated by optimization models would be the best solution for the underlying assumptions. Therefore, optimization model-generated schedules are to be validated to check their feasibility and system performance when applied to real world. Hence, the overall motivation of the research study is to develop an validation methodology for production scheduling (that can be adopted to the use case of steel ladle logistics), by using a technique that can replicate the real-world dynamics of system.

1.4. RESEARCH QUESTIONS

As a result, the preliminary research objective of the present study is to identify the validation practices adopted by researchers in the context of production scheduling optimization models and ultimately identify the literature gap. A robust Systematic Literature Review (SLR) framework has also been defined to accomplish the phase. The hypothesis defined in the study is that, simulation modelling techniques can be adopted for validation of production scheduling, as it possess an ability to replicate real world by integrating stochastic process parameters.

To achieve the research goal and realize the motivation, authors have broke down the objective into the preliminary research question and various sub-questions. The research questions, detailed below, provided an foundation from investigating relevant literature for review to proposing an validation methodology using DES as research outcome.

MAIN RESEARCH QUESTION:

How historical data and simulation methods can be used to evaluate the decision support systems for steel ladle logistics optimisation?

SUB-RESEARCH QUESTIONS:

1. **Sub-RQ1 (Knowledge Question):** What are the techniques used to validate the decision support systems in the context of production scheduling?
   Motivation: To review the literature for identifying predominant validation methods applied to the the decision support systems of production scheduling. Interpretation of the prevailing approaches assists in identifying the literature progress, and research gap in the context of validating decision support systems. Insights derived from this review help to advance state-of-the-art methods or practices by making them more efficient and robust.

2. **Sub-RQ2 (Knowledge Question):** What are the challenges, bottlenecks and limitations of involved with the current techniques used to validate the decision support systems?

Motivation: It is fundamental to gain insights into the challenges, limitations, and bottlenecks associated with the current validation techniques, as it aids in proving and emphasizing the research gap and critical issues related to the sustainability of steel plants.

3. **Sub-RQ3 (Knowledge Question):** What are the Key Performance Indicators (KPI's) that effects the sustainability of steel plants?
   Motivation: The question helps to identify the key performance indicators of the steelmaking process that influence the change in the sustainability index of steel plants. It is essential to review the literature in this context, as it helps to develop a robust validation methodology that quantifies the production schedule's energy efficiency and sustainability.
4. **Sub-RQ4 (Design Question):** How to adopt the Discrete event simulation model along with historical data to evaluate the optimization models?
   Motivation: It is crucial to analyze the practices discerned in the literature for adopting discrete event simulation for validation purposes. It helps to find the proven methodologies for integrating simulation models along side optimization models and ultimately evaluating the production schedules generated by optimization models.
5. **Sub-RQ5 (Design Question):** How to design an discrete event simulation model?
   Motivation: This question helps to comprehend the approaches adopted by the researchers and practitioners to develop a discrete event simulation model in the context of production scheduling. It helps to identify the prerequisites, process parameters, and best practices to develop an efficient simulation model. As a result, the review assists in designing the architecture of the simulation model.

This approach aims to identify the bottlenecks, optimization areas, feasibility of schedules, and additional constraints or boundary conditions within the optimization model. The outcomes proposed in this study would provide inspiration and useful insights for successive studies and practitioners. To be specific, the application of DES in evaluating the decision support systems in the production scheduling domain.

1.5. METHODOLOGY

In order to address the research questions and fulfill the research goals a high-level execution methodology was designed as depicted in Figure 1.4. Initially, to identify the predominant trends and literature gap, a comprehensive SLR was carried out. Subsequently, a detailed research implementation methodology was formulated to evaluate a decision support system. In the initial stage of problem understanding, processes regarding steel ladle logistics were identified and a conceptual model describing the required entities, operations, and activities was designed. In order to convert the conceptual model into a computerized simulation model, SimPy was selected as the relevant implementation package.

Upon verification of the conceptual model, a high-level simulation model was designed to simulate the main processes of the conceptual model. Subsequently, the simulation model underwent iterative development to include all the details defined in the conceptual model. It was also verified in each development phase to match & verify the behaviour with the real-world dynamics.

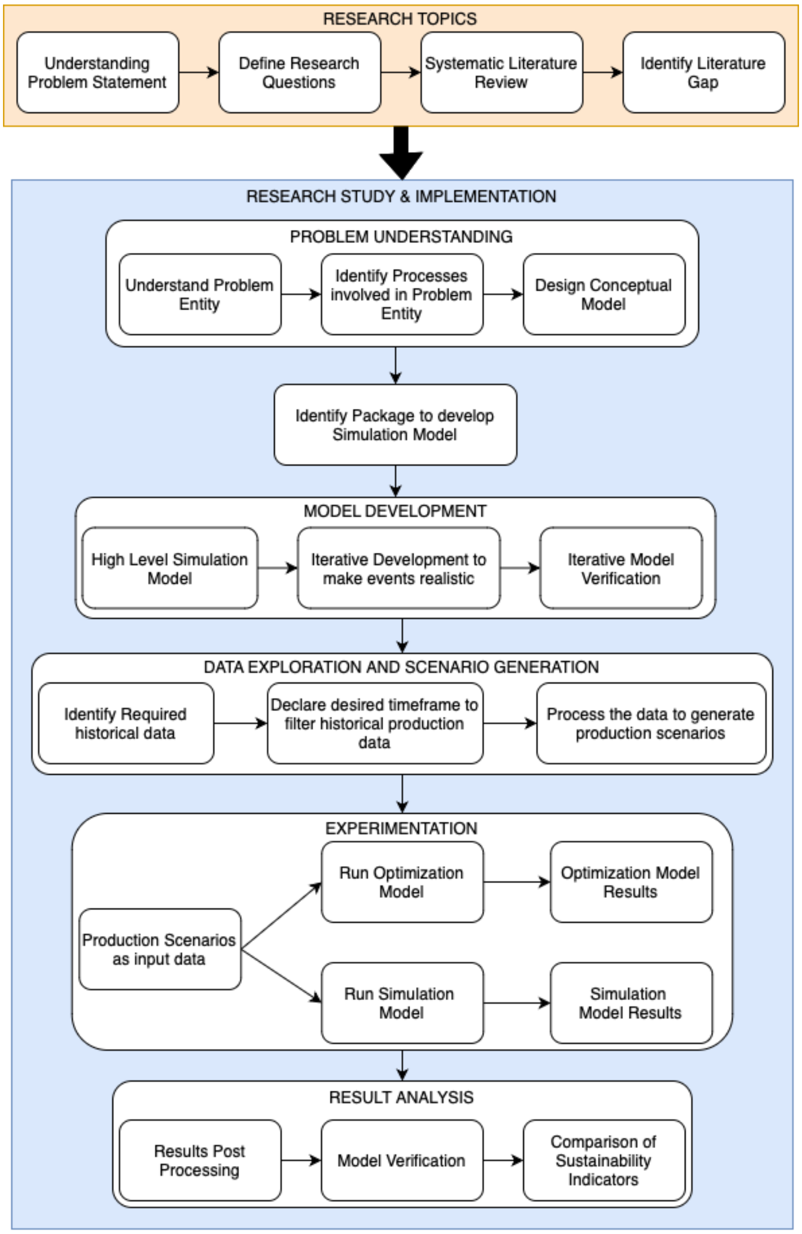

Figure 1.4: Flowchart Summarising Research Project Methodology

Following the development of DES model, experimentation was carried out, which primarily focuses on execution of optimization and simulation models. So, historical data from TSNL was utilised to generate production scenarios which is an prerequisite for execution of both the models. Results from the optimization model and simulation model were further analyzed to conduct feasibility analysis and compare the sustainability indicators to understand the system performance.

1.6. THESIS STRUCTURE

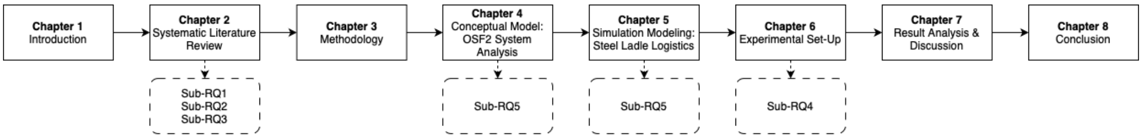

Figure 1.5: Research Structure

The present thesis is structured into eight chapters, organized as follows: Chapter 1 paves the way for the reader by explaining the research background (Steel Making, Steel Ladles, Steel Ladle Logistics), defining the research motivation and problem context, formulating research questions by emphasizing the research goal. Chapter 2 describes the SLR methodology adopted to address the sub-research questions 1-3. The chapter delineates the predominate themes, trends and potential research gap from literature. Chapter 3 describes the motivation to follow an solution method, primary methodology adopted to develop the solution method and theoretical concepts related to discrete event simulation. Chapter 4 presents the conceptual model of steel ladle logistics by explaining the findings from system analysis. This chapter detail's the processes involved in steel ladle logistics, the way they are triggered and dispatching rules involved to carryout the process. Chapter 5 explains the simulation model development phase. This chapter details the modules developed in different phases and the processes modelled in each phase. Furthermore, Chapter 6 focuses on the experimental set up designed for the study. The chapter explains the data required for the experimentation of simulation model and experimental approach. Subsequently, Chapter 7 explains the results of experimentation, analysis and discussion of results. Finally, Chapter 8 concludes the research study by highlighting the contributions, answers to research questions, limitations and future recommendations. Figure 1.5 provides an visual representation of research structure indicating the sub-research questions addressed in corresponding chapters.

2

SYSTEMATIC LITERATURE REVIEW

2.1. METHODOLOGY

In order to carry out the systematic literature review, Scopus[1] was considered as the primary literature database, owing to its intricate search engine and extensive repository of scientific articles. [16, 50] The advanced search feature of Scopus was utilized to generate custom search queries by including pre-defined keywords and their synonyms related to context of each research question. The pre-defined keywords are categorized as follows:

- Steel-making, Steel making, Steelmaking,
- Sustainability, Energy Efficiency
- Simulation, Discrete Event Simulation
- Ladle Dispatching, Ladle Scheduling, Logistics / Scheduling
- Steel Ladle
- Decision Support Systems / Decision Making
- Refractory
- Advanced Analytics

These keywords, in combination with the logical operators 'OR' and 'AND' are expedited to generate search queries corresponding to the research context of validating decision support systems of production scheduling by incorporating energy efficiency and sustainability of steel plants:

Search Queries Corresponding to Sub-Research Questions 1 & 2:

- ("decision support system" OR ("decision making")) AND ("steel making" OR "steel ladle logistics")

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[1] `https://www.scopus.com/home.uri`

- ((“optimal ladle dispatching” OR “optimal logistics schedule” OR “optimal logistics”) AND (“simulation” OR “simulation methods”))
- ((“validation” OR “evaluation”) AND (“decision support system” OR “decision support tool”) AND “production scheduling”)
- (“Optimization” AND “scheduling” AND (“steel making” OR “steel ladle logistics”))

Search Query Corresponding to Sub-Research Question 3:

- ((“Energy Efficiency” OR “Sustainability”) AND (“steel making” OR “steelmaking” OR “steel-making” OR “steel ladle logistics” OR “ladle logistics” OR “ladle dispatching” OR “ladle scheduling”))

Search Queries Corresponding to Sub-Research Questions 4 & 5:

- ((“Simulation” OR “discrete event simulation” OR “digital twin” OR “simulation methods”) AND (“steel making” OR “steel ladle logistics” OR “ladle dispatching” OR “steel ladles”) AND “optimisation”)
- ((“historical data” OR “operations data”) AND (“simulation” OR “simulation modelling” OR “simulation methods” OR “discrete event simulation”) AND (“steel making” OR “scheduling”) AND (“optimization” OR “optimisation”))

The search queries were concerning the presence of pre-defined keywords in either title or abstract or author keywords of literature in the preliminary retrieval phase. It resulted in 2230 research articles which were further screened for context suitability.

The selection was first confined to Journal and Conference papers, filtering to a total of 2037 articles. Going further in the process, the selection was confined to the articles relevant to the fields: Computer Science; Engineering; Business, Management and Accounting; Mathematics; Decision Sciences, Energy, Chemical Engineering, Materials science, Environmental Science yielding a sum of 1953 articles.

Furthermore, articles were filtered to fulfill the additional criteria of publication from 2013 and written in the English. This refinement reduced the pool of articles to 1316. Subsequently, the process of excluding the literature lacking full-open access, inaccessible through UT LISA services[2] and articles in the press was carried out which resulted in a list of 374 articles.

The final phase of selection process was to exclude the literature by analyzing the title and abstract of articles if they are not relevant or out of the research objectives and context. The overarching complete literature selection process is illustrated in Figure 2.1 and selection criteria established to curate the final literature collection for review is out-listed in Table 2.1

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[2] https://www.utwente.nl/en/service-portal/services/lisa/

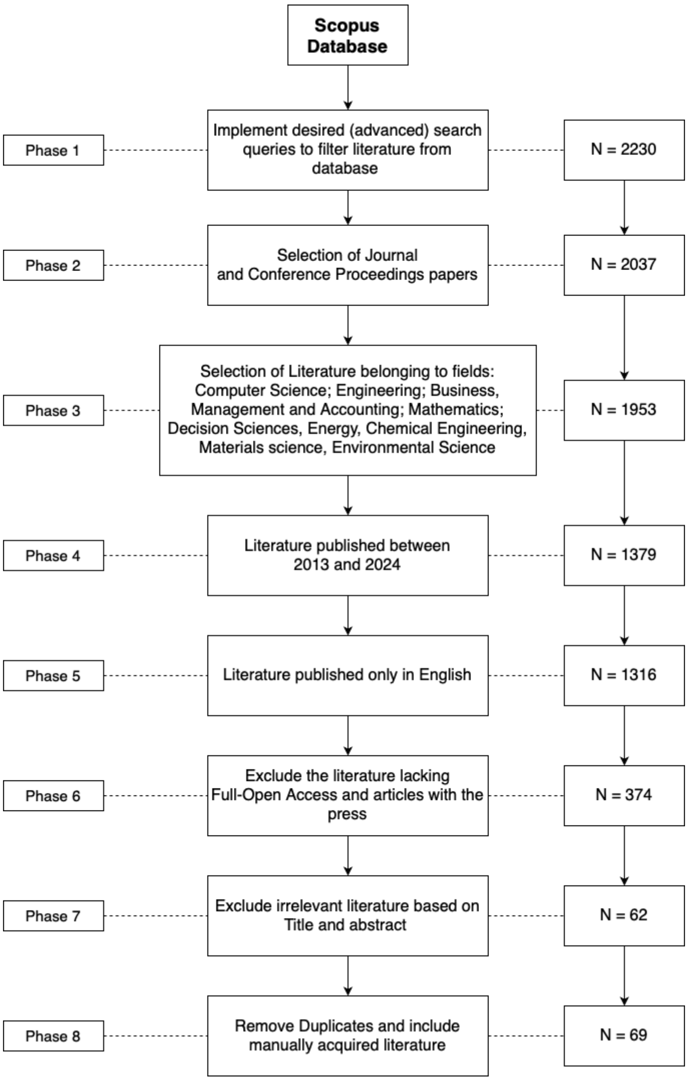

Figure 2.1: Literature selection process for SLR

Table 2.1: Overview of literature selection criteria used in SLR.

Selection Criteria	**Decision**	**Phase**
Title or Abstract or Author's Keywords of literature possess any of pre-defined keywords	Inclusion	Phase 1
Literature is an Journal or Conference Proceedings article, categorized to relevant field	Inclusion	Phase 2
Literature Published in English	Inclusion	Phase 5
Manually Acquired Literature	Inclusion	Phase 8
Literature published before 2013	Exclusion	Phase 4
Literature lacking full open access, not accessible through UT LISA services, article in press	Exclusion	Phase 8

Title or Abstract of literature irrelevant to research context	Exclusion	Phase 7
Duplicates of an original article	Exclusion	Phase 8

2.2. DECONSTRUCTING THE RESEARCH LANDSCAPE

The present section explains the research landscape of Decision Support Systems related to the production scheduling of the steel-making process in three different directions. In subsequent sections, prominent themes and trends observed in the literature are summarized and conventionally presented. In-detail aspects and critical review points derived during the process are comprehensively facilitated in Table A1. The table highlights the objective, motivation, models developed (if any), evaluation metrics (if any), KPIs evaluated, application industry, and area of every reviewed literature.

2.2.1. TEMPORAL DISTRIBUTION OF LITERATURE

The analysis and deconstruction of the literature were initialized by examining their temporal distribution. The analysis aided in identifying the historical trends related to production scheduling in the scientific landscape. As depicted in Figure 2.2, articles were classified by publication year. The pace of scientific contributions was sinusoidal from 2013 to 2019. Whereas from 2020, there is a sudden surge in distribution, indicating the interest of researchers in studying decision support systems, energy efficiency of manufacturing processes, logistics, etc. This sudden surge in the temporal trend can be due to the motivation from United Nations Sustainable Development goals, energy crisis, efforts to limit the green house emissions.

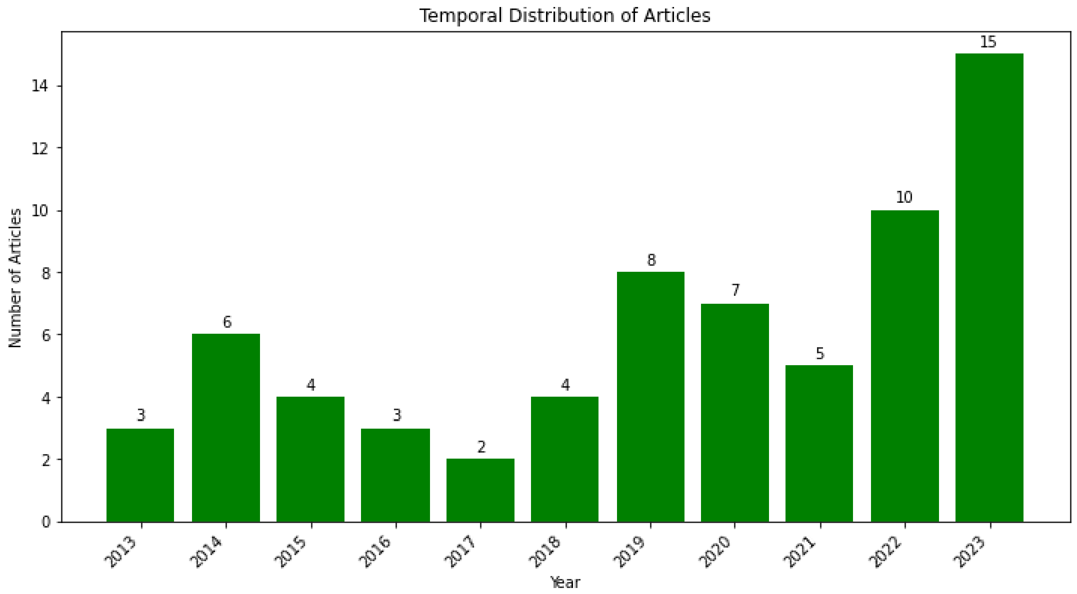

Figure 2.2: Year Wise distribution of selected literature

2.2.2. JOURNAL DISTRIBUTION OF LITERATURE

The succeeding analysis focuses on the journal distribution of the reviewed literature, selected across various topics such as Production Scheduling, Supply Chain Planning, Logistics, Iron and Steel industry, Steel-making process, and Steel ladles. Table 2.2 indexes all the articles with their research topic, journal of publication, number of citations, and impact factor of journal (as of 2022). Journal Distribution in Table 2.2 indicates that the majority of articles hold comparatively higher citation scores and are published in journals with elevated impact factors, underscoring the research topic as a significant theme in the scientific landscape. Notably, the analysis also underlines the lack of scientific contributions addressing the optimization of steel ladle logistics, suggesting a potential area for future research exploration.

Table 2.2: Journal Distribution Overview of Literature selected for review

Research Topic	Article	Journal	# Citations	Impact Factor
Iron & Steel Production	Chattopadhyay, R., Chakraborty, S., Chakraborty, S., [18]	Decision Making: Applications in Management and Engineering	81	13.93
Steel-making Scheduling	Su, P., Zhou, Y., Wu, J., [80]	Journal of Cleaner Production	0	11.1
Steel-making	Schneider, C., [75]	Journal of Cleaner Production	9	11.1
Iron & Steel Production	Norbert, R., Kim, J., Griffay, G., [64]	Journal of Cleaner Production	9	11.1
Production Scheduling	Zampou, E., Plitsos, S., Karagiannaki, A., et al. [97]	Computers in Industry	30	10
Production Scheduling	Liu, Z., Sampaio, P., Pishchulov, G., et al. [58]	Computers in Industry	33	10
Steel-making	Roy, R., Adesola, B., Thornton, S., [71]	International Journal of Production Research	34	9.2
Supply-Chain Planning	Tsolakis, N., Zissis, D., Papaefthimiou, S., Korfiatis, N., [89]	International Journal of Production Research	28	9.2
Steel-making	Gasser, A., Boisse, P., Rousseau, J., et al. [29]	Composites Science and Technology	18	9.1
Iron & Steel Production	Zeng, Y., Xiao, X., Li, J., et al. [98]	Energy	40	9
Production Scheduling	Plitsos, S., Repoussis, P., Mourtos, I., et al. [68]	Decision Support Systems	38	7.5
Validation	Borenstein, D., [13]	Decision Support Systems	72	7.5
Production Scheduling	Kibzun, A., Rasskazova. V.,[48]	Automation and Remote Control	0	0.7
Ladle Design	Berntsson, F., Wikström. P.,[12]	International Journal for Computational Methods in Engineering Science and Mechanics	0	0.236
Production Scheduling	Krenczyk, D., Paprocka, I.,[49]	Materials	4	3.4
Iron & Steel Production	Lee, S., Lee, G., Moon, S., Yoon, Y., [54]	IET Generation, Transmission and Distribution	0	2.5
Steel-making Scheduling	Wang, D., Liu, Z., Chen, L., Wei, M., Li, Y., [91]	ACS Omega	0	4.1
Steel-making	Matino, I., Colla, V., Maddaloni, A., et al. [62]	Water (Switzerland)	0	3.4
Steel-making Scheduling	Lee, M., Moon, K., Lee, K., Hong, J., Pinedo, M., [53]	Journal of the Operational Research Society	0	3.6
Steel Ladle Logistics	Ruela, V., Van Beurden, P., Sinnema, S., Hofmann, R., Birkelbach, F., [72]	IEEE Access	0	3.9
Steel-making	Hernández, J., Onofri, L., Engell, S., [40]	Metallurgical and Materials Transactions B	3	3.0
Steel Ladles	Liu, W., Pang, X., Li, H., Sun, L., [57]	International Journal of Advanced Manufacturing Technology	4	3.4
Supply-Chain Planning	He, D., [39]	Computational Intelligence and Neuroscience	2	3.12
Steel-making	Barral, P., Pérez-Pérez, L., Quintela, P., [11]	International Journal of Thermal Sciences	5	4.5
Steel-making	Stavropoulos, P., Panagiotopoulou, V., Papacharalampopoulos, A., et al. [78]	Designs	10	2.74
Steel-making	Andreiana, D., Acevedo Galicia, L., Ollila, S., et al. [6]	Processes	3	3.5

Production Scheduling	Lang, S., Kuetgens, M., Reichardt, P., Reggelin, T., [51]	IFAC-PapersOnLine	4	-
Supply-Chain Planning	Mazurenko, A., Kudriashov, A., Lebid, I., et al. [63]	Eastern-European Journal of Enterprise Technologies	2	0.402
Steel-making	Degrassi, G., Parussini, L., Boscolo, M., et al. [20]	SN Applied Sciences	7	2.6
Production Scheduling	Cheng, C., Lin, S., Pourhejazy, P., Ying, K., Lin, Y., [19]	Mathematics	3	2.4
Steel-making	Jawahery, S., Visuri, V., Wasbø, S., et al. [45]	Metals	8	2.9
Production Scheduling	Agárdi, A., Nehéz, K., [3]	Academic Journal of Manufacturing Engineering	0	0.257
Steel-making & Ladle Dispatching	Han, D., Tang, Q., Zhang, Z., Cao, J., [36]	IEEE Access	10	3.9
Iron & Steel Production	Ahmad, I., Arif, M., Cheema, I., et al. [4]	Sustainability (Switzerland)	11	3.9
Steel-making & Casting Scheduling	Armellini, D., Borzone, P., Ceschia, S., et al. [8]	International Transactions in Operational Research	15	7.2
Steel-making	Branca, T., Fornai, B., Colla, V., et al. [15]	Materiaux et Techniques	10	0.9
Steel-making	Holappa, L., [41]	Metals	99	2.9
Steel Ladle Logistics	Tesselaar, W., Sluiter, A., Peekel, M., [87]	METEC-ESTAD proceedings	-	-
Steel Ladle Logistics	Chatterjee, S., Senguttuvan, A., Biswal, A., et al. [17]	METEC-ESTAD proceedings	-	-
Simulation & Optimization	Borodin, V., Bourtembourg, J., Hnaien, F., et al. [14]	International Journal of Modelling and Simulation	9	2.9
Supply-Chain Planning	Ohmori, S., Huang, Q., Yoshimoto, K., [65]	Journal of Industrial Engineering and Management	1	0.437
Supply-Chain Planning	Zhuang, Y., Zhang, N., Wang, S., et al. [100]	Sustainability (Switzerland)	1	3.9
Supply-Chain Planning	Lu, J., Nie, X., [59]	IOP Conference Series: Earth and Environmental Science	1	-
Steel-making	Shahin, A., Labib, A., Emami, S., et al. [76]	TQM Journal	8	0.646
Steel-making	Backman, J., Kyllönen, V., Helaakoski, H., [9]	IFAC-PapersOnLine	9	0.324
Steel-making	Sun, L., Jin, H., Li, Y., [83]	IEEE Robotics and Automation Letters	16	5.2
Production Scheduling	Fan, Y., Anwar, S., Wang, L., [25]	IEEE International Conference on Control and Automation, ICCA	0	-
Steel Ladle Logistics	Hou, A., Jin, S., Harmuth, H., Gruber, D., [42]	JOM	16	2.6
Steel-making	Zhao, X., Bai, H., Hao, J., [99]	Energy Procedia	13	-
Steel Ladle Logistics	Huang, B., Ma, Z., Tian, N., et al. [43]	MATEC Web of Conferences	1	-
Steel-making	Su, L., Qi, Y., Jin, L., [79]	International Journal of Simulation Modelling	12	2.9
Steel-making	Fanti, M., Rotunno. G., Stecco, G., et al. [26]	IEEE Transactions on Automation Science and Engineering	25	5.6
Steel-making Scheduling	Hao, J., Liu, M., Jiang, S., Wu, C., [37]	European Journal of Operational Research	39	6.4
Steel Ladle Logistics	Reinders, G., [70]	TUDelft	-	-
Steel-making	Sun, L., Luan, F., [81]	IFAC-PapersOnLine	4	0.324
Steel-making	Sun, L., Luan, F., [82]	IFAC-PapersOnLine	5	0.324
Simulation & Optimization	Figueira, G., Almada-Lobo, B., [28]	Simulation Modelling Practice and Theory	205	4.2
Steel Ladles	Drózd-Ryś, M., Harmuth, H., Rössler, R., [23]	Proceedings of the Unified International Technical Conference on Refractories, UNITECR 2013	0	-
Production Scheduling	Pan, Q., Ruiz, R., [67]	Omega (United Kingdom)	145	8.673
Steel-making	Worapradya, K., [92]	South African Journal of Industrial Engineering	5	0.5
Supply-Chain Planning	Guillaume, R., Marques, G., Thierry, C., et al. [34]	Engineering Applications of Artificial Intelligence	5	8
Supply Chain Planning	Maheut, J., Sabater, J., [60]	Journal of Industrial Engineering and Management	-	-
Production Scheduling	Xiong, J., Xing, L., Chen, Y., [96]	International Journal of Production Economics	184	12
Iron & Steel Production	Jiang, Z., Zhang, X., Jin, P., et al. [46]	International Journal of Energy Research	14	4.6
Steel Ladle	Liu, W., Sun, L., Ding, J., et al. [56]	IFAC Proceedings Volumes	9	-
Production Scheduling	Ghezail, F., Pierreval, H., Hajri-Gabouj, S., [30]	Computers & Industrial Engineering	38	7.9

Simulation & Optimization	Almeder, C., Preusser, M., Hartl, R., [5]	OR Spectrum	70	2.7
Production Scheduling	Goren, S., Sabuncuoglu, I., [32]	IIE Transactions	38	2.6
Production Scheduling	Ouelhadj, D., Petrovic, S., [66]	Journal of Scheduling	634	2.0
Production Scheduling	Goren, S., Sabuncuoglu, I., [31]	IIE Transactions	99	2.6
Production Scheduling	Liu, L., Gu, H., Xi, Y., [55]	International Journal of Advanced Manufacturing Technology	67	3.4

2.2.3. DISTRIBUTION BASED ON KEYWORDS

The subsequent part of the deconstructing research landscape dealt with the analysis of selected article's keywords. Analyzing in this context would be beneficial to find the dominant themes in the literature, as keywords indicate the scope, primary focus, and research topic of the articles. Figure 2.3 exhibits a word cloud developed using Python libraries, which showcases all the keywords observed in the selected articles for review. The size of words in the word cloud is directly proportional to the frequency of the keyword prevalent in literature. The most observed keywords in the literature that were also observed to be included in the search queries were: "scheduling", "simulation" and "steel-making". Apart from those included in search queries other most repeated keywords were: "optimization", "energy", "production", "iron", "logistics", "carbon", "emissions", "control", "integration", "process", "management". The frequent prevalence of these keywords emphasize the trend of optimization, energy efficiency in research landscape. It is noteworthy that a handful of articles are observed to have no author keywords. As a result, they were excluded from this part of the analysis.

Figure 2.3: Word Cloud of Keywords from selected Literature

2.2.4. DISTRIBUTION BASED ON RESEARCH TOPIC

The after-most part of the research landscape deconstruction analyzed the industries adopting and applying decision support systems for scheduling purposes. This analysis helps to identify the prevalent themes in literature, such as the focus of researchers, research progress in the present context, etc. Figure 2.4 exhibits a bar graph emphasizing the application industries observed in the selected literature. The most prevailing application industry was steel-making, production scheduling at manufacturing plants and assembly chains, followed by supply chain planning, and . It was found that, relatively fewer scientific contributions were observed applying decision support systems in the context of steel ladle logistics.

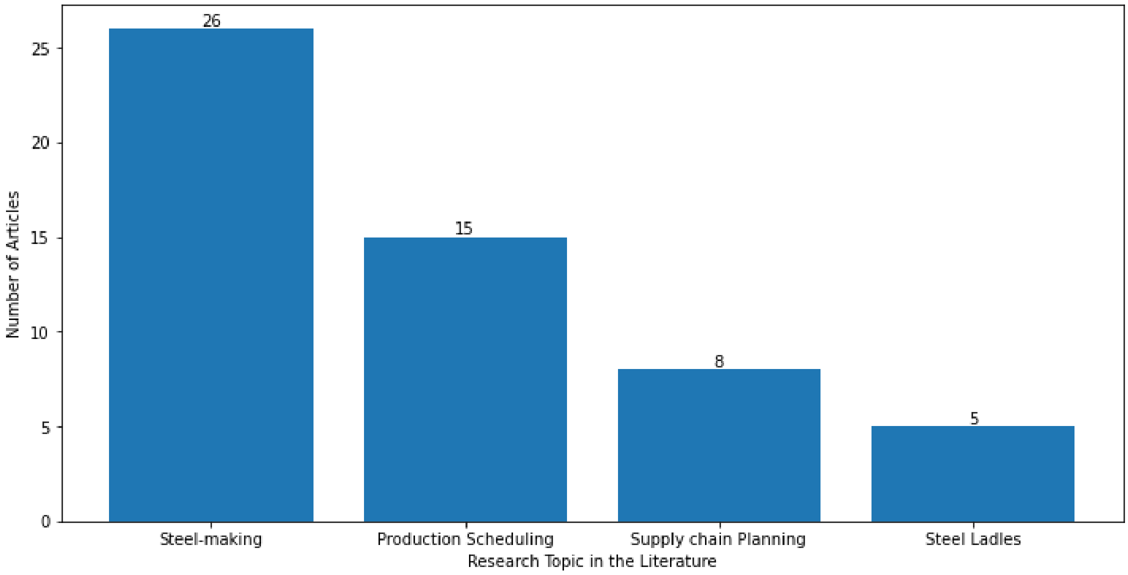

Figure 2.4: Research Topic Based Distribution of selected Literature

2.3. PREDOMINANT THEMES IN LITERATURE

In the quest for identifying and understanding the trends in methods used for the validation of decision support systems within the fields of production scheduling and logistics, this section demonstrates the underlying themes and practices from the scientific landscape or literature. The researchers adopt innovational techniques and methods for the development and validation of decision support systems for distinct operations in the steel-making process. Given the rapidly changing operational environments of the steel-making process, it is extremely important to examine the validation methods used in distinct scenarios to deliver comprehensive insights into their robustness, scalability, and adaptability.

To deliver the findings systematically, they are categorized into four subsections, each focusing on specific themes regarding validation methods used for decision support systems in production scheduling, overall steel-making process, and production scheduling across other industries.

2.3.1. ANALYSIS OF DECISION SUPPORT SYSTEM APPLICATIONS

The foremost subsection aims to describe a comprehensive overview of the application areas that prevailed in the research landscape concerning decision support systems of production scheduling. It consolidates the domains and scenarios in which decision support systems are studied and adopted to leverage the energy efficiency of the processes. This exercise is conducted to identify the advancements in the research of decision support systems concerning steel ladle logistics.

A noteworthy portion of the literature has focused on the decision support systems for optimal production planning in manufacturing plants and assembly lines [3, 19, 32, 34, 48, 60, 67, 68]. The primary objective of the reviewed literature was to transmute the production processes as energy and cost efficient systems. The developed optimization models were observed to generate optimal flow production plans, accurate real-time schedules, minimizing the idle status of machines and in some cases to make it no-idle scheduling.

During the literature review a significant theme was identified concerned with the supply chain process of manufacturing industries. Researchers have devised decision support systems aiming to generate cost and energy-efficient logistics schedules, ensuring timely delivery of end products from the production plant to the retail stores [3, 34, 39, 59, 68, 100].

As we further streamline our focus towards the review of the literature concerning the application of decision support systems for the steel-making process, three prevalent themes were observed:

- One of the themes was to develop the optimization models for generating optimal (in terms of energy efficiency and sustainability) steel production schedules to make the process cost-efficient, environmentally safe, and reduce make-span [82, 83, 92].
- The Second theme addresses the complexity inherent in generic steel-making scheduling, aiming to generate near-optimal schedules in practical time frames. [8, 26, 79, 81].
- The final theme encompasses studies in specialized cases, such as equipment shutdown strategies, scheduling byproduct gases in furnaces, real-time control of furnaces, avoiding uncertain scheduling, cost reduction and energy-saving approaches by analyzing energy consumption behavior [37, 45, 46, 54, 80, 91, 98, 99]. We have also found an special case of re-scheduling steel ladle routes with-in production sites when they come across adverse events such as machine failures, breakdowns or delays [57].

Finally, as we hone in on the analysis of decision support systems for steel ladle logistics, very few scientific contributions were prevalent in the landscape. These studies concentrated on formulating steel ladle logistic schedules considering the time dependencies and energy correlations of the processes ultimately making the schedules energy efficient [36, 56, 72]. By considering a fixed wear rate of refractory linings, thermal behavior of the ladle was also predicted while generating optimal solutions of to the ladle dispatching problem [72].

2.3.2. SUB-RQ1: ANALYSIS OF VALIDATION TECHNIQUES

In order to effectively assess the robustness, adaptability, and scalability of decision support systems, researchers employ various validation techniques and evaluation methodologies based on project-specific scope, and applications. This subsection concentrates on demonstrating dominant and trending validation techniques and evaluation methodologies prevalent in the literature.

While reviewing the literature concerning decision support systems of production scheduling, we identified a dominant theme in validation techniques. A substantial portion of the literature is observed to employ a comparison of energy-related or time-related metrics by carrying out computational or numerical testing of the models. One of the noteworthy approaches was to compare the system performance of optimization algorithms or solution method against the State-of-the-art models previously contributed in the literature [8, 32, 36, 37, 67, 81, 83]. Similarly, authors have also validated the models by juxtaposing the computational performances against the baseline models employed while building the models (i.e., researchers have worked to develop a new algorithm or improvised algorithm referring to a baseline) [19, 36, 45, 46, 48, 68, 80, 82, 83, 92, 98].

Conversely, a recent trend in conducting case studies as a validation method is evident in a few articles. Researchers adopting this method have considered the manufacturing, assembling, or logistics industry as the focal testing unit. Operational parameters (Such as time-related, energy-related, and temperature-related parameters of the processes) are acquired from the testing unit for computationally testing the models. Subsequently, schedules or decisions suggested by the model are compared with those of the manual or human-computer-generated schedules [36, 39, 43, 54, 57, 60, 83, 91].

In contrast to the computational testing and case study validation methods, a modest collection of scholarly works has also adopted the practical implementation of schedules or decisions recommended by the model in the production environment of the industry. [68]. This practical application adopts, validating the model by comparing the energy, resources, or time consumption estimations with the actual results in the plant.

Furthermore, a noteworthy validation technique is observed in a limited collection of State-of-the-Art scientific contributions focusing on steel and iron production processes. Researchers have adopted simulation techniques to validate the production schedules generated by the decision support systems. One such technique implicates the use of a simulation tool[3], to visually inspect the discrete event flows according to the schedules recommended by the model [46, 56]. Moreover, researchers also employed discrete event simulation to assess the practical feasibility and evaluation of the optimal schedules [26].

2.3.3. SUB-RQ1: ANALYSIS OF SIMULATION METHODS USED FOR VALIDATION

This subsection describes the approaches and strategies adopted by the researchers to apply simulation methods to validate decision support systems and optimization models. It also analyses and delivers the application contexts of using simulation modeling either for validation or verification.

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[3] Simulation tools possessing the capability of visualizing discrete event flow such as ARENA, FlexSim, CPLEX

A handful of articles are identified to be using simulation tools for visual inspection or validation of the schedules generated by decision support systems [37, 46, 56, 57, 79]. In the context of production scheduling, we observed that researchers are adopting simulation tools to visualize the production processes according to schedules generated by the models. Owing to this approach, researchers would be able to quantify the feasibility of schedules in a production environment.

Additionally, a note-worthy trend is observed in the validation of decisions generated by mathematical models in the context of steel ladles using CFD Simulations[4]. Researchers working on the optimization of the steel-making process would validate the designs and decisions initially by simulation before applying the changes to the production environment [12, 23]. It helps to identify the effects of decisions or changes in the steel-making process (preheating, stand-by, transportation time-span, etc.) on the system performance.

Furthermore, a sophisticated application of DES was identified for the validation of production scheduling of the steel-making process. Researchers have integrated simulation modules alongside the optimization modules of decision support systems for proactive scheduling[5] and reactive scheduling[6]. It would be helpful for correcting the pathways or schedules due to unforeseen failures, delays, and machine breakdowns [26].

2.3.4. SUB-RQ3: ANALYSIS OF SUSTAINABILITY INDICATORS

Owing to the constantly changing environment and climatic conditions of the world, cutting-edge applications & technologies are being developed are focused on leveraging sustainability indicators in the manufacturing industries use case. In steel and iron-making industries, research is being progressed to make the processes energy efficient and sustainable by analyzing the optimization areas and feasibility to optimize.

In this regard, predominant trends and themes are identified in the literature, where decision support systems are devised to transform the steel-making process into energy-efficient and sustainable. Sustainability indicators addressed by researchers in different directions and use cases align closely to those outlined by World Steel Association [95].

According to Worldsteel Association [95], a notable trend was observed across the global steel plants to carry out concerted efforts towards producing *'environmentally sustainable'* or *'green'* steel within their respective timelines. Consequently, the research endeavors to optimize the steel-making processes aims to address the sustainability indicators outlined for steel plants by Worldsteel Association [95].

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[4] Computational Fluid Dynamics (CFD) simulation is a numerical method of virtually simulating fluid motion and thermal behavior using computational techniques to estimate the feasibility and usability of design in a production environment CFD Simulation - Siemens

[5] Proactive Scheduling is the kind of process that considers the adverse future events (that can possibly happen during production process) in the model while generating schedules.

[6] Reactive Scheduling is a process of correcting the schedule during production process to adapt to the adverse events during action.

Consequently, World Steel Association has systematically classified the sustainability indicators into three categories: “Environmental Performance”, “Social Performance”, “Economic Performance”. Within each category, numerous indicators are outlined along with their significance, preliminary assessment approaches and connection to United Nations Sustainable Development Goals (UNSDG).

Table 2.3: Sustainability Indicators Outlined by World Steel Association [95]

Indicator	**Definition**	**Relevant UNSDG**[7]
Intensity of CO_2 Emissions	This indicator calculates the mass of CO_2 emitted for a tonne of steel casted in steel plant.	SDG 7; SDG 13
Intensity of Energy	This indicator calculates the amount of energy consumed in GJ for producing a tonne of steel cased in steel plant.	SDG 7; SDG 13
Efficiency of Material	This indicator calculates the amount of crude steel and by-products against the final product (solid & liquid).	SDG 12
Environmental Management System	This indicator calculates the ratio of man power working in steel production facilities registered with environmental management system.	SDG 3; SDG 6; SDG 11; SDG 12; SDG 14; SDG 15
Frequency of Injured Lost Time	This indicator calculates the total number of hours lost due to injuries and fatalities per million working hours.	SDG 3; SDG 8
Employee Training	This indicator calculates the number of training days for each employee per year.	SDG 4; SDG 8
Investments	This indicator calculates the amount of investments made by a steel plant for research and development to introduce new processes and products.	SDG 1; SDG 8; SDG 9
Distributed Economic Value	This indicator calculates the value distributed to society interns of direct and in-direct economy.	SDG 1; SDG 8; SDG 9

It is noteworthy to mention that researchers or practitioners adopting sustainability indicators as in Table 2.3, must identify the processes in their research domain that influence the indicators. The World Steel Association has formulated these set of sustainability indicators with the intention to drive the steel industries towards fulfilling the United Nations Sustainable Development Goals (UN-SDG). Sustainable goals being fulfilled by each sustainability indicator can be found in detail in [95]. These sustainability indicators may also serve as a key attribute in Digital Product Passports[8] of each end product produced in the steel plant.

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[7] Please find the United Nations SDG’s and their explanations at `https://sdgs.un.org/goals`

[8] In order gain more insights on The EU Digital Product Passport, please refer to `https://www.tudelft.nl/en/`

2.4. DISCUSSIONS AND IMPLICATIONS

The present study aimed to conduct a thorough systematic literature review in three different directions: Application areas of decision support systems, research progress in the context of steel ladle logistics, and validation methods used to evaluate the schedules generated by the optimization models. In this section, limitations of current practices, literature gap, possible future perspective of Advanced Analytics, impact, limitations of literature review, and future recommendations are presented.

2.4.1. SUB-RQ2: LIMITATIONS OF CURRENT VALIDATION TECHNIQUES

The primary objective of this study was to identify the validation techniques adopted by the researchers to evaluate optimization models concerning production scheduling. This objective was accomplished, and the dominant trends found in the selected literature are detailed in Section 2.3.2. In this subsection, a comprehensive elucidation is furnished concerning the limitations, bottlenecks, and challenges associated with the existing validation methods.

- **Comparison of Computational Times:** Most of the researchers carrying out studies to solve the generic production scheduling problems (Section 2.3.1) are adopting comparison against State-of-the-art algorithms or base-line models as the validation technique. The comparison will be carried out against the computational time recorded for generating optimal schedules by both models. This approach just addresses the computational time, but not the optimality of the schedule and feasibility of generated schedules.

- **Feasibility Analysis:** In the reviewed literature, many studies have made efforts to solve generic scheduling problems faster by reducing computational time. Most of the solution methods would be heuristics with authors' assumptions and compromises. So the model could not address the adverse effects (failures, delays, etc.) in the production process ultimately pointing to the feasibility. But, to the best of our knowledge, most of the studies have not carried out the feasibility analyses to check if the model-generated schedules are feasible in more realistic dynamics of system.

- **Usability in the Real-world case:** In scientific landscape, most of the researchers are comparing the model performance against base-lines or State-of-the-art for validation purposes. Even though the researchers are reporting the performance of the model based on the reduced computational time recorded for generating optimal schedules it cannot be an robust validation. That's because, the reduced computational time doesn't guarantee the usability of the schedule in the production site. That can be due to the assumptions, constraints, boundary conditions etc., considered during building the optimization algorithms.

`stories/articles/a-digital-product-passport-for-a-circular-economy.`

2.4.2. LITERATURE GAP

One of the objectives of the literature review is to discern and emphasize the literature gaps pertinent to steel ladles, steel ladle logistics, optimization models for steel ladle dispatching, and methodologies for validating production schedules. This subsection underscores the identified gaps in the literature to furnish direction for future research and potential practical implementations.

- As delineated in Section 2.3.1 and illustrated in Table 2.2, very few scientific contributions are determined in the context of steel ladles. Notably, within the literature, few have addressed the direct mechanical design aspect of steel ladles. Precisely, a mere three articles have been found handling the critical issue of enhancing energy efficiency among steel ladle logistics [36, 56, 72].

- As observed in the literature, a large portion of the optimization models formulated for assorted production scheduling scenarios have predominantly remained as theoretical constructs without practical enactment. This phenomenon emanates from the absence of robust validation methodology capable of carrying out feasibility analysis on model-generated schedules [53, 97]. One prominent solution methods contributed to the literature and practically implemented in practice was [8].

- Few researchers have considered utilizing simulation tools for visually inspecting the schedules generated by the optimization models. However, this approach is not deemed a robust or accurate validation method [26]. This implication is primarily due to the inherent limitations of schedules generated by underlying heuristics possessing specific assumptions, i.e., the assumptions and simplifications of the heuristics fail to replicate the real-world production scenarios accurately.

- One of the scholarly articles in the literature has implemented discrete event simulation with stochastic process parameters in conjunction with optimization models to validate production schedules [26]. Authors have also considered steel ladle logistics as a part of steel making process while developing optimization model and simulation model. However, it is noteworthy that the authors were not concerned with in-depth details of steel ladle logistics.

2.4.3. INTEGRATION OF DISCRETE EVENT SIMULATION AND OPTIMIZATION MODEL

This subsection delves into one of the primary objectives of the review, which is to identify the integration feasibility of optimization models and discrete event simulations. Upon comprehensively exploring the literature on the Scopus database, a limited number of research and review articles are found discussing the integration of optimization models and discrete event simulation models in the context of production scheduling. Notably, these articles have contributed theoretical approaches, frameworks and generically discussed the integration feasibility of discrete event simulation models along side optimization models. However, practical implementation of findings to a specific use case was lacking.

- Almeder. C., et al. [5] have presented a generic framework aimed at the integration of optimization models and discrete event simulation models by emphasising the motivation and demonstrating the integration. As per the authors, discrete event simulation models represent complex systems as a non-linear & stochastic model, closely resembling real-world cases. However, an optimization model is a simplified version of these systems. By iterative generation of schedules using an optimization model and quantifying system performance using a DES model, efficient schedules can be produced. The authors emphasized that, following this approach can potentially enhance the performance of system.
- Borodin, V., et al. [14] have researched presenting possible connotations concerning the multifaceted realm of simulation optimization coupling. The authors generalized the coupling phenomenon into three overarching cases: Simulation encapsulated into Optimization; Hybrid Simulation Optimization without Encapsulation; and Optimization encapsulated into Simulation. To demonstrate all three cases, the authors have adopted the software products ARENA for simulation and CPLEX for optimization.
- Figueira. G., et al. [28] have presented the possible combination of simulation methods and optimization methods to develop hybrid optimization-simulation methods. The authors have meticulously detailed various optimization models and simulation methods by emphasizing their capability and integration feasibility. The taxonomy suggested in the literature provides valuable insights for designing a couple between optimization and simulation models.
- Krenczyk, D., et al. [49] and Backman. J., [9] underscores the necessity of integrating Optimization models, Discrete event simulation, Artificial Intelligence, and probability theory to enhance the flexibility of production scheduling. The authors emphasized that integration is crucial for realizing the objective of smart factory operations as a part of a shift towards the Industry 4.0 paradigm. The authors highlight that the methodology would be highly beneficial in achieving on-time production in the context of limited production line resources.

2.5. SHIFT IN CONCEPTUAL PERSPECTIVE

In order to briefly encapsulate the research implications and authors' perspectives in the context of optimization model development and validation, we have designed a conceptual shift. The shift, as sketched in Figure 2.5, emphasizes the theoretical perspective from a retrospective examination of the Past to the Future in the context of steel ladle logistics.

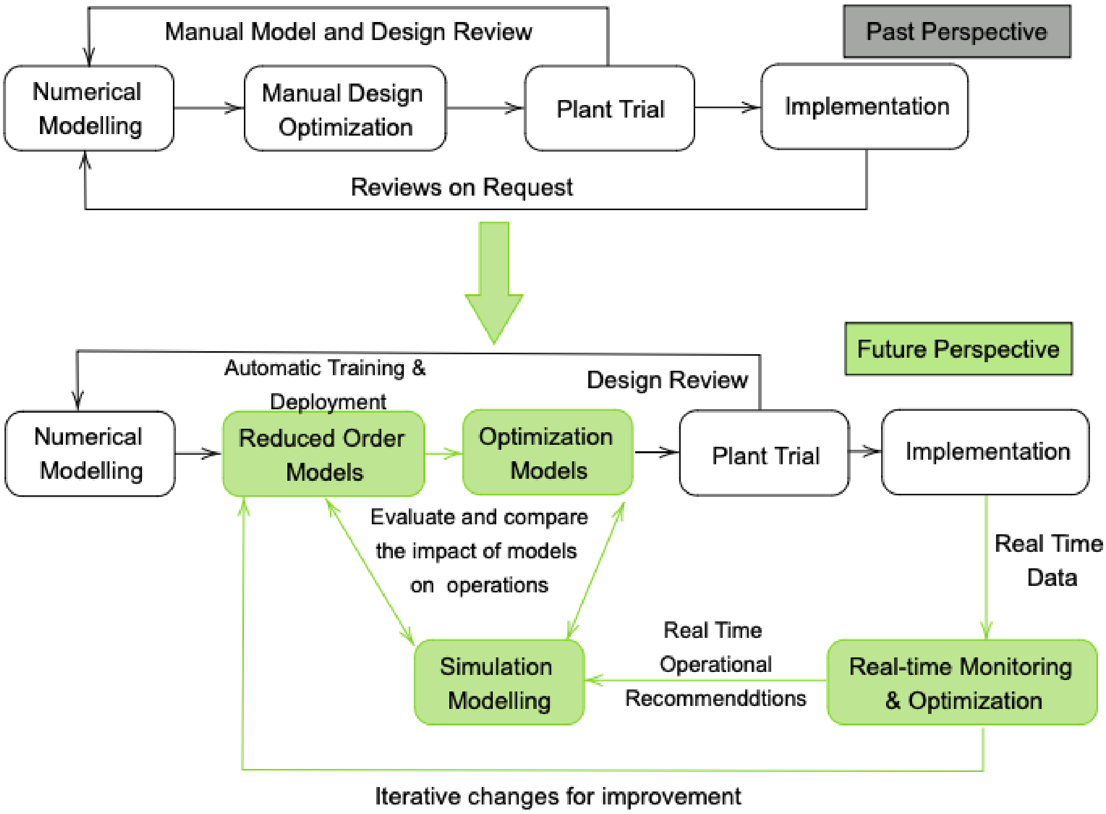

Figure 2.5: Shift from Past to Future Perspective in DSS development

In the examined literature, the predominant approach in the context of decision support systems entails a development perspective characterized by few key stages. Initially, the process being researched for optimization would be converted into a numerical model. Subsequently, the designed model will be optimized manually, often incorporating intricate operations or sub-processes. Upon accomplishing the manual optimization phase, the model would be deployed into the production site for plant trails, typically serving as solitary formal validation.

During the plant trials, the model's performance would be monitored for any vulnerable situations and issues. This manual iterative cycle continues until the issues are eliminated and satisfactory performance is achieved. At this moment the model is deemed ready for practical implementation at the production site. Thereafter, a support group would be working on stand-by for reviewing the model design upon request from the stakeholders to ensure quality assurance and refinement efforts.

The future perspective elucidated in literature represents an extrapolation from the past perspective. In contrast to the manual design optimization and empirical plant trails, the future perspective underscores the model development by adopting Reduced Order Models, Optimization Models, Simulation modeling, and real-time monitoring optimization.

Following, the Numerical Model of the process being researched would be converted into a

Reduced Order Model (ROM)[9] by automatic training and deployment. ROM can be further integrated into optimization models to estimate the impact of decisions on the processes. The reduced order models and optimization models would be evaluated by adopting a simulation model to compare the impact of models on system performance. The primary reason behind adopting simulation modeling is due to the ability to replicate real-world logistical dynamics with more details than the optimization.

Similar to the past perspective, as optimization models achieve satisfactory performance levels, they would undergo plant trials to verify for any issues with the model and then they would be deployed into production sites for practical implementation. Subsequently, data generated at the production site would be trained into a real-time monitoring & optimization system for generating operational recommendations and iterative changes for improvement.

2.5.1. DISCRETE EVENT SIMULATION FOR VALIDATION

This subsection provides a concise synopsis of Discrete Event Simulation, explaining its working capabilities, and significance in the context. The reviewed literature offers vital insights into the importance of validation and the use of simulation modeling for this purpose. These insights underscore a potential research direction for future endeavors.

According to the Simulation course module offered at the University of Twente and Law, A., [52], Discrete Event Simulation is a technique of replicating the operational behavior of a real-world system, process, or facility. It models the operations of a system as a flow of events in time such that each event occurs at a specified instance of time and mutates the state in the system.

The field of Discrete Event Simulation boasts numerous applications owing to its versatile capabilities. Borodin, V., et al. [14] has generically summarized these applications, thereby streamlining their adoption to various research domains or industries:

- Given an operational sequence of a system, it can check for the feasibility of the occurrence of events by gauging the viability of events within system constraints and boundary conditions.
- In order to enhance the optimal performance of analytical models and support iterative improvements for upholding the accuracy over time.
- To derive informed decisions regarding implementing or discarding a solution generated by analytical models, optimization models, or decision support systems.

Simulation modeling also holds another intelligent application. In order to understand it clearly, it is essential to comprehend the validation and its dimensions. According to [13], validation refers to the process of examining the agreement between optimization or analytical model behavior to real-world systems in a specific domain or industry. Validation generally has two dimensions:“Verification”, “Substantiation”. Verification is a method of examining the extent to

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[9] Reduced Order Models are generalized mathematical representation of complex processes that aims to replicate primary behavior subsequently reducing computational complexity[61].

which a model is faithful to the process conception and if the conception is valid. On the other hand, Substantiation addresses the computer model of the application domain to determine whether it possesses a satisfactory level of accuracy in representing the modeled system.

As a result, considering the requirements of validation process, discrete event simulation can emerge as a viable technique to validate solutions of an optimization model, given its capabilities.

2.6. CONCLUSIONS OF LITERATURE REVIEW

2.6.1. IMPACT OF THE LITERATURE REVIEW

The results and findings derived from the current literature review have substantial implications for future endeavors and impact in the scientific landscape.

During a thorough examination of existing literature, key patterns, trends, and themes have been discerned in the context of decision support systems applied to manufacturing and production domains. Upon consolidating the critical reviews of selected literature, the literature gap (as in Section 2.4.2) has been identified to guide researchers in future endeavors. The literature gap underscores the potential for research in implementing optimization models for steel ladle logistics.

Furthermore, efforts can be made to adopt Discrete event simulation for validation purposes of optimization models. If the research can progress in this direction, a robust evaluation framework can be designed for validating the results generated by optimization models. The development of such a framework can be a potential contribution to the research landscape as it fills the gap between theoretical models to their practical implementations.

2.6.2. FUTURE RECOMMENDATIONS

Consolidating the findings and literature gap from the study several recommendations are drafted for future research endeavours and directions as follows:

- Due to limited research on steel ladle logistics, optimization models can be developed in this context to make the process energy efficient and sustainable.
- Discrete Event Simulation can be adopted for validating the results of decision support systems and optimization models.
- Sustainability Indicators framed by World Steel Association can be adopted by steel industries to gauge the sustainability of decisions generated by optimization models.
- A robust validation framework can be developed by adopting simulation modelling and sustainability indicators for evaluating the results of optimization models.

3

METHODOLOGY

This chapter delineates the methodology adopted in the current research study, elucidating its various phases in detail. In the research landscape, methodology serves as a comprehensive framework directing overall research endeavors, ensuring efficiency, effectiveness, and robustness in attaining its goals or objectives.

The current chapter is branched into three sections to deliver a complete recapitulation of research methodology: the Analysis Methods for Manufacturing Systems, the Simulation Modelling Research Methodology, and the SimPy Package of Discrete event simulation sections. The first section delves into various analytical methods that can be employed in the domain of manufacturing systems (specifically production scheduling) to evaluate or compare their design or optimization. Following this, the subsequent section describes the methodology that is conducive to designing a simulation model. The section furnishes a detailed explanation of the sequential stages involved in developing a simulation model. The final section elucidates the technicalities of discrete event simulation furnishing a foundation for comprehending the technical intricacies in further chapters.

3.1. ANALYSIS METHODS FOR MANUFACTURING SYSTEMS

Designing a solution method for the optimization problem becomes significantly more intricate while prioritizing energy efficiency as the primary objective, compounded by design questions.

Upon designing or optimizing a manufacturing system, it is imperative to undergo analysis based on the objective: *"To evaluate the manufacturing system or compare alternative manufacturing system to decide upon the better system."*. Literature review (Chapter 2) reveals that the comparative analysis will focus on juxtaposing the computational performance of the solution methods.

The solution systems designed for the manufacturing systems, are to be evaluated upon few criteria and performance indicators. Adan et al. [2] has emphasized such frequently adopted criteria and performance indicators: *Flow-time, Variation in Flow-time, Machine Utilization, Work in Progress Collisions.*

In order to quantify any of these criteria or performance indicators, numerous analysis methods can be adopted depending on the size, resources, or situation of the application industry. Adan et al. [2] has underlined a few analysis methods that can be adopted in the production scheduling context: In the initial stage of industry or manufacturing system design, only rough estimations of parameters can be made due to the unavailability of enough data. As the manufacturing plant comes into operation and data is collected periodically, more accurate or efficient calculations can be performed using simple queuing equations. Due to the limited range of applicability and inability to handle complex scenarios of manufacturing plants, advanced queuing theory embedded with stochastic process theory needs to be adopted.

However, the adoption of these methods requires extensive mathematical skills, resources, and substantial efforts. If case of the manufacturing plant possesses an extensive range and quantity of historical operational data, adopting discrete event simulation would be an efficient approach. The analysis methods are depicted in Figure 3.1 in chronological order based on the design process stage, the range of applicability, and the amount of data required.

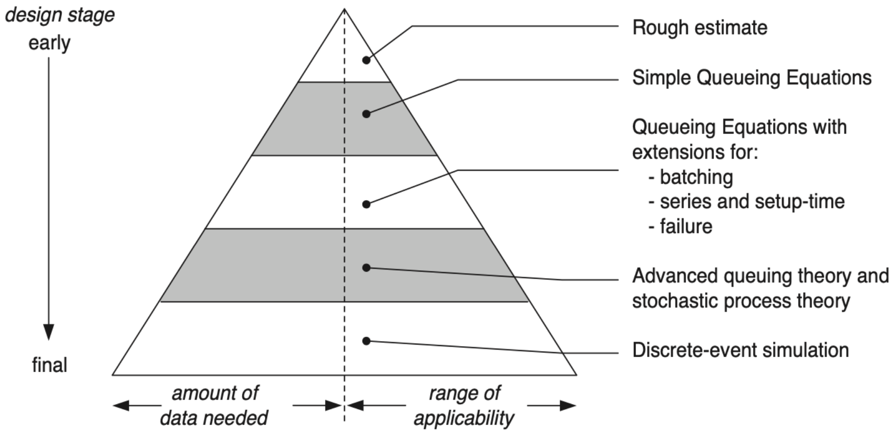

Figure 3.1: Analysis Methods for Manufacturing Systems (Source: Adan et al. [2])

Therefore, as the primary objective of current study is to evaluate decision support systems of a production scheduling problem using consistent performance indicators and evaluation criteria, among the array of analytical methods (Figure 3.1) Discrete-Event Simulation appears to be the most appropriate analysis method due to its broad applicability and availability of data. This preference is reinforced by the findings of the literature review (Chapter 2).

3.2. RESEARCH METHODOLOGY

Optimization models developed as a part of decision support systems possess certain extent of assumptions and simplifications, based on their research scope and resources. In general, real-world relationships between the system variables would be non-linear. Many optimization models consider then as linear approximations which might oversimplify the problem, potentially ignoring significant interactions. Kempf et al. [47] addressed that, in the context of production scheduling or logistics problem, researchers consider the process and transportation durations of system under study as deterministic, in contrast to their stochastic behavior in real-world operations. These parameters significantly influence the feasibility of production schedules and system performance when adopted in real-time.

Therefore, evaluating the optimization model would be a crucial phase in its development cycle and it turns yet more important if they are developed with the objective to make the operations sustainable and energy efficient. As a result, following methodology was adopted, in order to evaluate an optimization model in the current research study. It was designed by employing the methods and techniques found to be delivering promising results from the literature review (Chapter 2).

- **System Analysis:** It is the foremost phase, which involves conducting detailed analysis of the logistical system, tailored to the scope of the study. The motivation behind the phase is to identify key processes, operations of the system, their behavior in real time and resources required to carryout them. It is also imperative to understand the system constraints and dependencies that are required to be fulfilled to carryout each operation.
- **Simulation Modelling:** It is the phase of developing an discrete event simulation model, incorporating all the processes, policies and dispatching rules identified during system analysis. It is the general practice to declare the process parameters of the system as stochastic variables in simulation model to replicate the real world dynamics, in contract to their deterministic behavior in optimization model.
- **Integration:** For the simulation model, to evaluate the decisions generated by the optimization model, it necessitates an integration parameter between them. As the principle responsibility of simulation model is to evaluate the dispatching decisions of problem entity in real world dynamics, these decisions (being the key outputs of optimization model) serve as integration parameter and input for simulation model.
- **KPI Identification:** It is the phase of identifying the key performance indicators of the logistical system, which aids in carrying out comparative analysis on the system performance during evaluation. Depending on the logistical system, there could be an array of indicators addressing the impact on business, environment, economy etc., Based on the selection of indicators, outputs would be derived or post processed during execution.
- **Evaluation-Feasibility Analysis:** It is the initial phase of the conducting evaluation on optimization model generated outputs. The goal of this phase if to verify the feasibility of

dispatching decisions in respecting system and optimization constraints when executed in real-world dynamics.

- **Evaluation-Comparative Analysis:** If the model generated dispatching decisions are deemed to be feasible in primary evaluation phase, they undergo comparative analysis to analyse their effect on system performance. The primary motivation is to compare the effect of optimization model generated decisions on KPIs of the system when they are simulated through real world dynamics.

During both evaluation phases, the primary motivation would be to check the effect of stochastic process parameters on optimization model outputs against respecting system constraints, objectives and performance indicators. This approach aids in identifying the gap between the estimations of optimization model and anticipated to happen in real-world scenario. The insights from evaluation opens ideas for researchers in transforming their optimisation model into an efficient form.

3.3. SIMULATION MODELLING METHODOLOGY

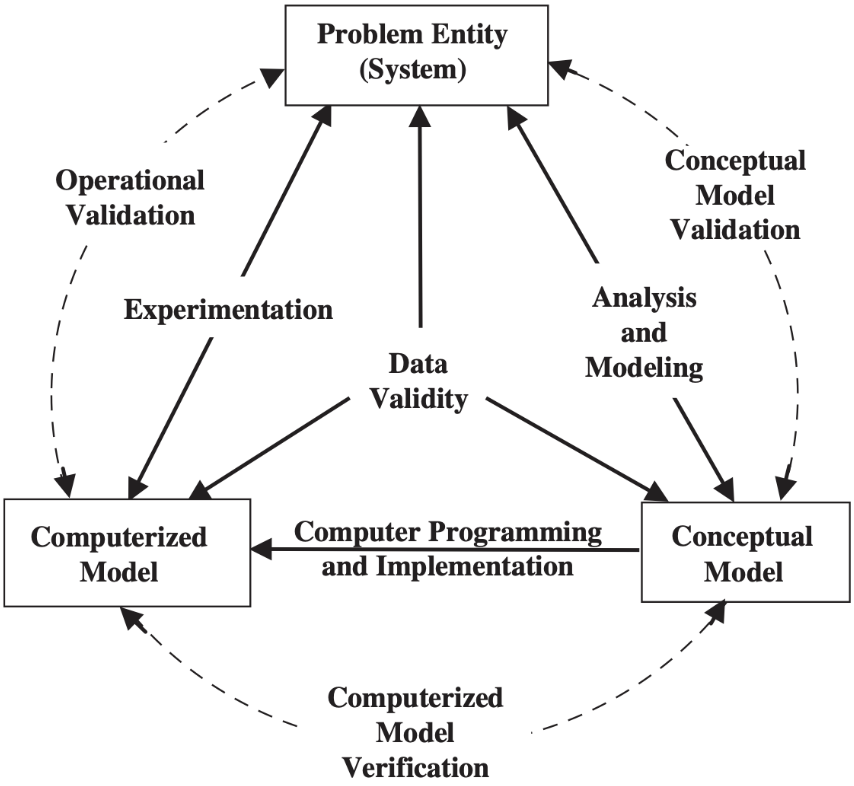

Figure 3.2: Simplified Version of Model Development Methodology: (Source: Sargent [73])

In the realm of simulation modeling, two predominant paradigms were guiding the model development process, both aimed at establishing the relationship between the Real World and the Simulation World. Sargent [74] in 1981 proposed a paradigm of simulation methodology in a simpler view (Figure 3.2). Over time, the same author elaborated on this paradigm, proposing a more intricate version of it with an in-detailed view of the methodology. But, Banks et al. [10] in 1988 meticulously assessed both paradigms by reviewing the works and concluded that the simpler paradigm more clearly represents the simulation methodology. Therefore, the simpler version of the paradigm is adopted for the current research study (as it appears to be suitable and appropriate for the case) and demonstration in this chapter. The overview of the Simulation Methodology relationship and process model is demonstrated in Figure 3.2 [73]

As it can be understood from illustration, the process model is divided into ten main phases [74]:

1. **Problem Entity (System):** It is the real-world system, encompassing its inherent characteristics, processes, policies, and events, which function as the subject of the research study's modeling phase. The motivation behind this phase is to understand the relationships among the system's processes or events and their possible behavioral outcomes.

2. **Conceptual Model:** The conceptual model serves as a replica of the problem entity developed for the objectives of the study. It can be developed as a graphical, mathematical, or logical representation tailored to the study requirements and available resources. Additionally, UML class and activity charts would also be adopted to enlighten the concepts behind problem instances with greater clarity.

3. **Computerized Model:** The developed conceptual model encompasses the specifications required for programming and implementing a simulation model on a computerized system. The computerized simulation model is the conceptual model developed as an Information Services application to facilitate the execution of required experiments. It can be developed either adopting simulation tools or programming languages.

4. **Analysis and Modeling:** Initially, the Problem entity to be studied using a simulation model will be conceptualized as a foundational model. This iterative process is addressed as the analysis and modeling phase. Subsequently, depending on the processes, ideas, and policies associated with the problem entity conceptual model will be refined.

5. **Conceptual Model Validation:** It is the phase of discerning the accuracy of the assumptions and theories underlying the conceptual model. Additionally, it entails an iterative evaluation of the congruence of the conceptual model (as it undergoes change) against the problem entity, aligning with the expected purpose of the study.

6. **Computer Programming and Implementation:** The specifications defined while conceptual modelling will serve as the implementation specifications for the development of the computerized simulation model on the designated computational source. The phase of adopting conceptual model to develop a computerized model is termed Computer Programming and Implementation.

7. **Computerized Model Verification:** It is the phase of evaluating or assuring that all the

model specifications defined in the conceptual model are accurately incorporated in the computer programming and implementation phase. Similar to the conceptual model validation phase, this phase also iteratively ensures alignment between conceptual and computerized models.

8. **Experimentation:** As the modeler or stakeholders attain a certain satisfactory level of confidence on the computerized simulation model, experiments would be conducted using numerous simulation scenarios. Conclusions regarding the computerized model will be made from the experimentation results of the simulation model.

9. **Operational Validation:** Operational validation represents a critical phase in the assessment of the simulation model's performance in experimentation. Its primary goal is to ascertain whether the simulation model behavior in the experimentation phase has a satisfactory level of accuracy for the expected purpose within the expected domain of applicability.

10. **Data Validity:** Data Validation is a continuous iterative process throughout the development cycle of a simulation model. Its primary motive is to ensure that the data being utilized for model development, experimentation, testing, and evaluation is accurate and adequate.

As described by Sargent [73]: *Face Validation* is a process of verifying the model and its functional behavior by an individual knowledgeable about the Problem Entity. *Structured Walk through* is a process of reviewing the model by presenting it to a peer member of the group to determine its correctness. *Trace* is a process of understanding the behavior of a model by observing the correctness of logic behind the model.

In conclusion, within the context of evaluating decision support systems, this simulation model development methodology offers a well-structured and efficient approach. This methodology guarantees a systematic approach to establishing specifications required for the development of the simulation model. By adhering to this methodology, the authors ensured that the final research artifact encompassed the essential processes, policies, and events pertaining to steel ladle logistics in line with the goals of the research study.

3.4. SIMPY PACKAGE - DISCRETE EVENT SIMULATION

Across the modelling and simulation landscape, there exists numerous forms of modelling and numerous ways of defining them. The authors of the study defined it as the technique of establishing a relation or correlation or association between the problem system and digital system.[1]

In the current study, SimPy[2] has been adopted as the modelling package for the objective of developing an simulation model of steel ladle logistics. Therefore, the technical concepts furnished later in this section are based on the documentations of SimPy Package. Similar func-

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[1] For more precise definitions, please refer to the text in Ackoff [1], Law [52]

[2] SimPy 4.1.1 Documentation `https://simpy.readthedocs.io/en/latest/contents.html`

tions or concepts can possess different working ability in any other simulation package.

3.4.1. BASIC CONCEPTS AND TERMINOLOGY

SimPy package is an event dispatcher working in an asynchronous manner. It has the ability to generate and schedule events at a specific simulation time. The package executes the events sorted by simulation time, increasing event id etc. It has three main components involved in the development and execution of simulation model: Environment (Section 3.4.2), Events (Section 3.4.3) and Process Functions (Section 3.4.4). Some of the basic concepts and terminology required to establish foundations of Discrete Event Simulation are:

- **System:** A stochastic dynamic system is the entity which transmutes its behavior by time and certain level of uncertainty.
- **State:** State represents the situation of system as the function of time.
- **Event:** Event is an occurrence prone to mutate the state of an system. For each event call, it triggers corresponding operation.
- **Operation:** Operation is a series of activities and each activity changes the state of a system.
- **Activity:** Activity is a small work unit with defined and fixed duration's. State changes are expected to happen at the initiation and termination of activities.
- **Process:** Process is a series of activities, operations, and events that triggers in a chronological order depending on the behavior of resource in the physical system.

3.4.2. SIMULATION: ENVIRONMENT

A Simulation Environment is a virtual space that manages the scheduling and processing of the discrete events by keeping track of the simulation time utilizing environment clock. SimPy Package offer two types of environments. Normal applications utilize generic ***Environment()***. It is an event-based simulation, which passes the time by stepping from one event to another. For the situations demanding real-time simulations, package provides ***RealtimeEnvironment()***. In this type of environment, simulation runs in synchronous with environment clock (i.e., wall clock time). An environment would be defined as:

env = simpy.Environment()
env = simpy.RealtimeEnvironment()

The package provides flexibility regarding the execution of simulation. An environment would be in running phase until it reaches any of the following termination conditions:

- **env.run():** Environment has no further events to execute.
- **env.run(until=t):** Environment clock reaches the specified timestamp. *env.timeout(t)* also has similar working function.
- **env.run(until=env.timeout(t)):** Environment terminates when the event in run() is processed.

The environment has a unit less simulation time. However it is up to the designer or modeller on how to gauge the time in environment. The package facilitates to derive the current simulation environment time by ***Environment.now*** function. The initial time of the environment would be *'0'* or an *initial_time* passed to the environment. The simulation clock in the environment would be mutated by ***'Timeout'*** events.

3.4.3. SIMULATION: EVENT

The SimPy Package facilitates various types of events. The event types that are frequently used in practice are:

- **events.Initialize:** Environment Schedules an event when a process function is created and starts the execution of event at specified timestamp.
- **events.Process:** Triggers the events or starts their execution, as defined in the generator function.
- **events.Timeout:** Timeout the environment to an assigned duration to change the state of entity.

Events in SimPy package are mostly similar to each other corresponding their behaviour. It is an class of the package which can be adopted to represent any kind of event. An event takes one of the following states: *'might happen*' (not yet triggered), *'to happen*' (triggered), and *'happened'* (triggered and processed).

3.4.4. SIMULATION: PROCESS FUNCTION

In the SimPy package, Process Functions are the plain python generator functions responsible for execution of a simulation model. They would define the behavior of system by yielding the instances of events. These functions would also aid in storing the list of events and tracks the current simulation time.

The generator function being called using the process event expects *'env'* class instance an mandatory parameter or argument. Once all required process functions are defined, they can be instantiated using their objects. A general practice and package obligation is to instantiate the environment in the initial stage as it need to be passed numerous times while defining everything else in the model.

The process function will be triggered in two steps:

- Process Function is to be called to create a generator object. This step will not execute any of the code in the function yet.
- The second step is to create a instance of process function. And then pass the environment and generator function to it. An example of it is as below:

env = simpy.Environment()
env.process(generator_function(env))

3.4.5. SIMULATION: RESOURCES

The SimPy package often addresses resources as *'Shared Resources'*, as they provide an abstraction for model processes interaction. The process functions have numerous instances and resources would be an congestion to sort and queue them for the future use. SimPy provides three major resources categories:

- **Resource:** Instances that can be assigned to a limited number of process events at a given point of time.
- **Containers:** Instances that can represent creation and consumption of an identical bulk of entities. It can be either continuous or discrete.
- **Stores:** Instances that facilitates the creation and usage of python objects. For example, it can monitor, numerous identical resources by alloting them to a store.

4

CONCEPTUAL MODEL: OSF2 SYSTEM ANALYSIS

This chapter describes the insights found through system analysis of OSF2 at TSNL, carried out in parallel to the SLR (Chapter 2). The motivation was to identify the processes involved in steel ladle logistics, resources required, process & transport durations and ladle routes between processes etc., as they standout to be the important aspects of research study. Section 4.1 describes the layout of OSF2 plant explaining the placement of all steel making installations, transport modes and transport routes. Section 4.3 explains the logistical cycle of steel ladles, phases in cycle and activities triggered in each phase of the cycle. The final section 4.4 explains the transport equipment's being used at OSF2 and the routes followed by them to move ladle for the operations.

4.1. OSF2 PLANT LAYOUT

One of the main objectives of research study is to develop an DES model of steel ladle logistics. In order to achieve this, it is obligatory to understand the steel-making resources, OSF2 layout and routing of steel ladles at OSF2 plant of TSNL.

Figure 4.1 illustrating the OSF2 layout was designed by referring to TSNL Documentation [86], Pronk [69] and Reinders [70]. The steel-making installations outlined in Figure 4.2, are situated in two halls at OSF2 plant, namely: **'Casting Bay 1'** and **'Casting Bay 2'** (*Giethal 1 & Giethal 2*). Casting Bay 1 facilitates Converter (CV) (CV21, CV22, CV23); Direct Sheet Plant (DSP); Stirring Station (SS) (SS23, SS22); VPB; and Pan Oven/Ladle Furnace(EN) (PO) (PO21); Warm Houd Stand/Reheating Stand(EN) (WHS) (WHS20); Tilting Stand (KS) (KS20). Casting Bay 2 houses WHS (WHS24, WHS25); KS (KS21, KS22); Slab Casters (CGM) (CGM21, CGM22, CGM23); PO (PO22); Slag Wagon; and SS (SS23). Among these resources, ladles, and cranes are categorized as movable resources capable & deemed to relocate within OSF2, whereas all other resources remain immovable and fixed at predetermined locations.

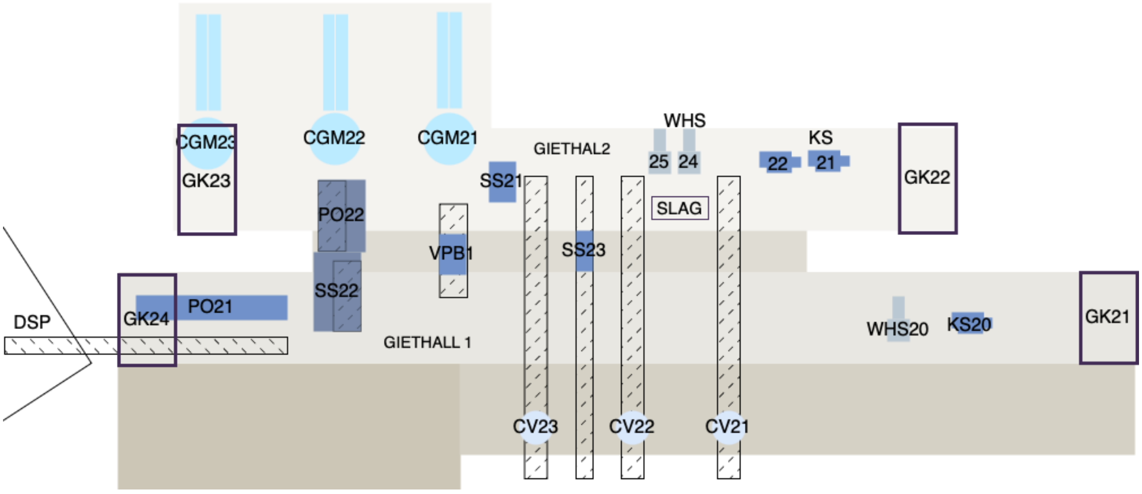

Figure 4.1: TSNL-OSF2 Layout with Installations and Bays

The UML diagram presented in Figure 4.2 presents an summarized overview of steel-making installations available at distinct locations (Figure 4.1) of OSF2 at TSNL. The OSF2 plant at TSNL facilitates numerous steel making resources of distinct categories and identities. As a result, it was assumed to be *'mixin'* stereotype. As each type of resource at the OSF2 plant possess distinct identity, they are assumed to be *'category'* stereotype. All these considerations are made by adopting the OntoUML methodology for UML modelling [1].

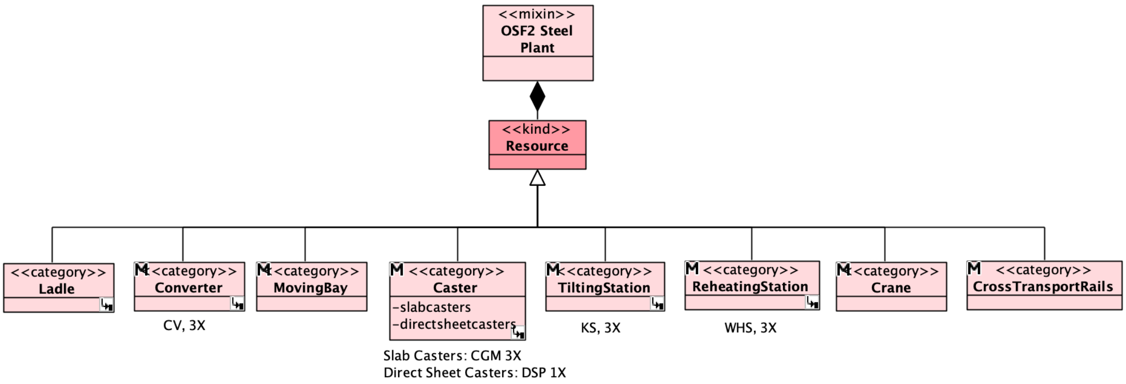

Figure 4.2: Overview of steel-making resources at OSF2

4.2. LADLE STATE THROUGH STEEL-MAKING CYCLE

According to the steel-making operational cycle at TSNL and Ruela et al. [72], a steel ladle undergoes through various thermal stages as depicted in Figure 4.3: **stage:FULL:** *tapping, secondaryMetallurgy*; **stage:CASTING:** *casting*; **stage:EMPTY:** *maintenance, transportation*; **stage:EMPTY_HEATING:** *reheating*.

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[1] In detailed explanation of OntoUML specification and the stereotypes can be found at `https://ontouml.readthedocs.io/en/latest/intro/ontouml.html`.

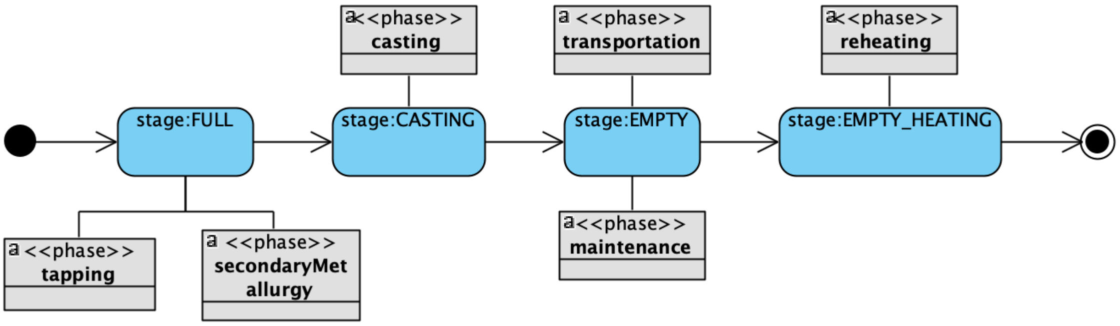

Figure 4.3: Steel Ladle State throughout the Steel-Making Cycle

4.3. STEEL-MAKING PHASES & OSF2 INSTALLATIONS

The current section delves into a comprehension of the logistical intricacies involved in steel-making processes and activities carried out to realize them. An introduction to steel ladles, along with an overview of steel-making involving steel ladles, are briefed in Section 1.2.

4.3.1. STEEL LADLE LOGISTICS

At TSNL, the steel-making process unfolds five principal phases. Throughout the process, a steel ladle plays a pivotal role, sequentially going through the phases to either transport molten steel or to prepare for receiving it. We assume that the process initiates from receiving molten steel at the converter location to reheating the ladle constitutes a single operational charge.

Each phase of the steel-making process would be carried out at dedicated locations equipped with specialized machinery: Tapping at Converters; Secondary Metallurgy at Vacuum degasser, ladle furnace, and stirring station; casting at casters; maintenance activities at tilting stands and reheating at reheating stands. The discrete events expected to happen within each steel-making phase are explained in the subsequent sections.

Among the phases illustrated in Figure 4.4 Tapping, Secondary Metallurgy, and Casting are categorized as *"Charged/full Ladle phases"* whereas Maintenance as *"Empty ladle phase"* and Reheating as *"Empty heating phase"*.

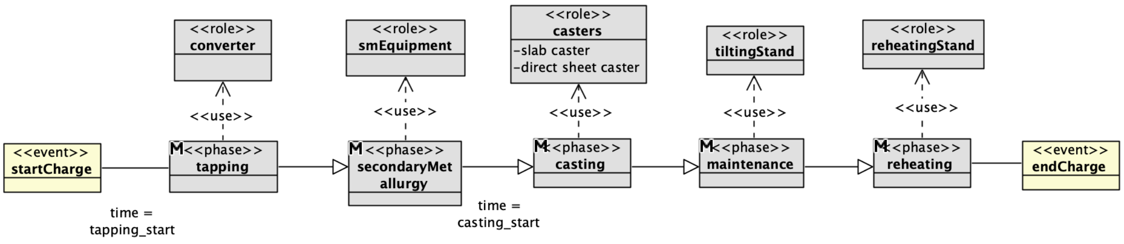

Figure 4.4: Overview of steel-making process at OSF2

One of the principal production goals of TSNL is to carry out continuous steel casting around the clock, expect when the casters are in maintenance. In order to achieve the goal, ladle dispatching schedules generated at OSF2 ensure that a ladle would be ready at the converter for receiving molten steel charge and the casting station to continue the casting at their specified/scheduled times. Therefore, as illustrated in Figure 4.5, a steel ladle rotates within the steel-making process to fulfill the continuous casting goal until it reaches End-of-the-Life (EOL) conditions. If a steel ladle reaches EOL, it moves out of production for major maintenance (briefed in Section 4.3.5).

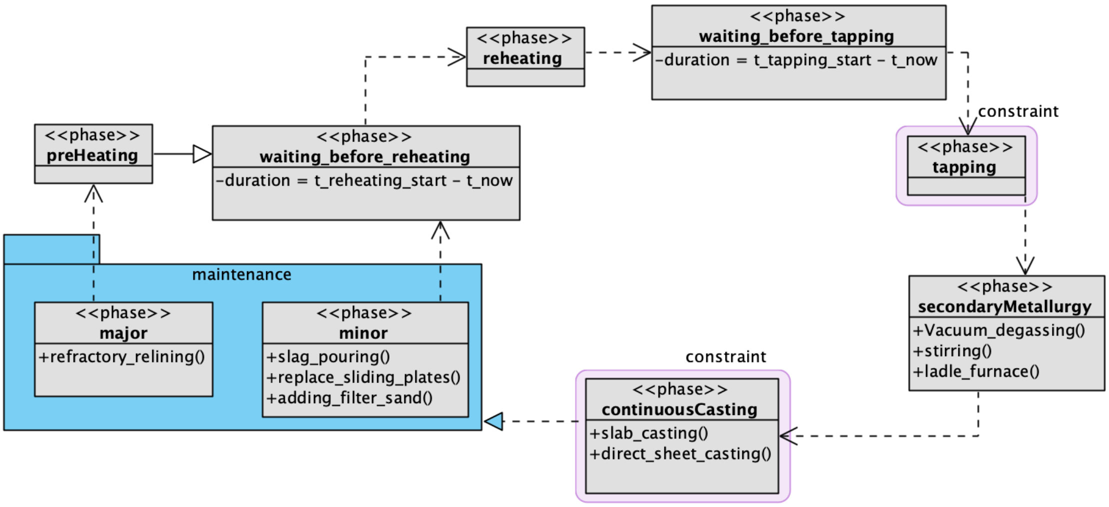

Figure 4.5: Overview of Steel Ladle logistical cycle at OSF2

4.3.2. TAPPING PHASE

Figure 4.4 illustrates that the tapping of molten steel into a steel ladle is carried out at the converter location. OSF2 at TSNL operates three Basic Oxygen Furnaces (CV), identified as CV21, CV22, CV23. As illustrated in Figure 4.1, these converters are installed in casting bay 1. The converter plays an crucial role in steel plants by converting carbon-rich hot metal (4.5%) received from blast furnace to low carbon steel(< 1.9%) [84].

The production staff operating at OSF2 are informed about the scheduled end time of converter operation for each steel charge. Consequently, they ensure the availability of a steel ladle at the converter location to receive the molten steel to carry out subsequent operations. A steel ladle starts moving towards the specified converter location based on the start time of tapping and transport duration, ensuring its arrival at the anticipated time. According to input from a stakeholder at TSNL and Reinders [70], the tapping duration at any of CV locations can be assumed fixed at *8.5 minutes*. Upon the successful conclusion of the tapping phase, the charged steel ladle is transported to the secondary metallurgy phase.

4.3.3. SECONDARY METALLURGICAL PHASE

The secondary metallurgical phase initiates upon the tapping of liquid steel into the steel ladle. As illustrated in Figure 4.4 and 4.5, secondary metallurgical treatments encompass a range of processes occurring within various installations categorized as three groups: VPB, SS, and PO.

As represented in Figure 4.1, these equipment's are installed in various locations across OSF2. The primary aim of this treatment is to refine the liquid steel, achieving the desired thermal and chemical composition necessary for casting into slabs or sheets.

The operations conducted at distinct secondary metallurgical installations may vary depending on various parameters such as the steel grade of charge, anticipated thermal state, and chemical composition of molten steel. Consequently, these parameters influence the sequence and duration of the operations. Additionally, the duration of these operations is dependent upon the available time before the ladle needs to be transported for the casting phase. Consequently, the duration of secondary metallurgical treatments is the time between the end of tapping and the start of casting the charge.

4.3.4. CASTING PHASE

Following the secondary metallurgical treatments, steel ladles undergo transportation to one of the casting locations. At OSF2, TSNL there are three Slab Casters: CGM21, CGM22, CGM23 (situated in Casting Bay 2) and one Direct Sheet Plant (situated in Casting Bay 1) . In the scenario of CGM, the steel ladle is conveyed to casting locations and connected to the ladle turret. Subsequently, as the ladle turret aligns with the desired position on top of the tundish, the bottom of the steel ladle is opened to facilitate liquid steel flow into the tundish for casting. Whereas in the case of DSP, an additional process is involved whereby the casted slabs are directly rolled out until they reach the desired sheet thickness.

The operators at OSF2 ensure the timely transportation of steel ladle to the casting location, assuring un-interruption in continuous casting. The casting duration, represents the time taken by the ladle to fill the molten steel in the tundish.

4.3.5. MAINTENANCE PHASE

As a steel ladle finishes casting, the ladle turret undergoes a rotation of 180° to facilitate another ladle to start casting. Subsequently, the emptied ladle is prepared for maintenance and remains on the turret until a crane is dispatched to the casting location for retrieval. As the cranes picks the steel ladle from casting location, it conveys the ladle to one of the tilting stands KS (from a selection of KS20, KS21, KS22) situated in ***Casting Bay 1 & 2*** of OSF2 (illustrated in Figure 4.1).

The maintenance phase initiates at the moment, the crane picks up the empty ladle at the casting location. While transporting to the tiling stand, the crane halts at the slag removal area for slag disposal. OSF2 has an area dedicated for facilitating slag ladles as wagons for pouring slag. After pouring slag, the transportation of the ladle to the tilting stand resumes.

As it reaches the tilting stand, operators carry out a series of operations tailored to the ladle condition: Removal of solidified slag, changing sliding plates, and adding filter sand to the ladle. The duration of the maintenance is contingent upon the fulfillment of required operations among those specified above. According to Reinders [70], the maintenance duration at OSF2 varies between *20 to 25 minutes*. The reliability and usability of this distribution is verified by an stakeholder at TSNL. After the maintenance phase, the ladle would be transported further for reheating.

4.3.6. REHEATING PHASE

After the completion of maintenance activities, the emptied steel ladle is conveyed to one of the reheating stations WHS (from a selection of WHS20, WHS21, WHS22). As illustrated in Figure 4.1, these reheating stations are situated in the ***Casting Bay 1 & 2***. The duration that a ladle needs to be reheated depends on several key parameters: *temperature of ladle before reheating, expected temperature for tapping, transport time to reheating stand, transport time to reach converter, and available time before tapping next charge.*

As illustrated in Figure 4.5, the logistical cycle of a steel ladle encompasses various phases, commencing from tapping to reheating. This cycle iterates until the ladle reaches end-of-the-life conditions, prompting its removal from production for major maintenance procedures.

4.4. OSF2 TRANSPORT MODES & ROUTES

4.4.1. TRANSPORT MODES

In the previous sections, various steel-making installations and their respective placements in OSF2 are discussed. The OSF2 plant employs two transportation modes in order to convey steel ladles through different installations for steel-making: Overhead transport by Casting Crane (GK) and ground-level transport by Cross Transport (CT).

OSF2 plant has four casting cranes: GK21, GK22, GK23, GK24. Casting cranes GK21 and GK24 are responsible of transmuting steel ladles in casting bay 1. Where as GK22 and GK23 are responsible for transport of them in casting bay 2. Additionally there are numerous cross transport rails in the plant. There are three CT rails, one at each converter to transport steel ladles and hot metal ladles. One CT to convey the steel ladle to and from the DSP caster. Each one of SS22, SS23, VPB1 and PO22 has one CT.

In order to calculate the transport duration of ladles between different steel-making installations, it is in deed required to know the drive velocities of casting cranes and cross transport rails. The values mentioned below are retrieved from Reinders [70] and verified their usability by an stakeholder at TSNL.

Casting Crane GK Drive Velocity: 90 m/min
Cross Transport CT Drive Velocity: 21.3 m/min

4.4.2. TRANSPORT ROUTES

With the current understanding of the installations and transport modes at OSF2 plant, it is significant to comprehend the transport modes and routes adopted to convey ladles between each operational phase.

- **Converter to Secondary Metallurgy:** Steel ladle tapped with liquid steel is transported to secondary metallurgical operations initially through CT until it reaches Casting Bay 1. Subsequently, the transport mode used is dependent on the location of the secondary metallurgical installation. It would often involve a combination of both CT and GK.

- **Casters to Maintenance:** Emptied steel ladle after casting would be transported to KS in two different ways. In the case of CGM casters, GK22 and GK23 are used. In the case of DSP casters, steel ladle would be first transported to one of the available CT in casting bay 1 through GK21 and GK24. Available CT is used to reach the casting bay 2 and from there one of the two casting cranes IGK22 and GK23) conveys it to tilting stands.
- **Secondary Metallurgy to Casters; Maintenance to Reheating; Reheating or Maintenance to Converter**: A combination of both CT and GK are used for transporting steel ladle to the casting location.

At the OSF2 plant, when ever a ladle needs to move between locations, the transport duration constitute the theoretical duration (computed using the velocities stated in Section 4.4.1) and practical waiting durations. It includes the duration a transport equipment requires to reach desired location. From the above specified list of transport routes, last three are within the scope of study as they fall under empty ladle operations. As the current study doesn't address the processes accomplished between tapping and casting the transport routes corresponding to them are excluded. Consequently, the waiting times corresponding to maintenance, reheating and tapping are extracted from Reinders [70]. The reliability of the values are conformed by an stakeholder at TSNL. These waiting durations facilitated in Table 4.1 are adopted in the Transport Duration module of DES model as explained in Section 5.3.3.

Table 4.1: Overview of Waiting durations (min) to be included with Transport durations of cranes and transfer cars

location	**KS20**	**KS21**	**KS22**	**WHS20**	**WHS24**	**WHS25**	**CV21**	**CV22**	**CV23**
CGM21	4.5	4.5	4.5	0	0	0	0	0	0
CGM22	4.5	4.5	4.5	0	0	0	0	0	0
CGM23	4.5	4.5	4.5	0	0	0	0	0	0
DSP	9.9	9.9	9.9	0	0	0	0	0	0
KS20	0	0	0	13	13	13	17.3	17.0	34.8
KS21	0	0	0	13	13	13	20	17.7	37.0
KS22	0	0	0	13	13	13	17	17	35
WHS20	0	0	0	0	0	0	8.8	14.7	13.1
WHS24	0	0	0	0	0	0	13.5	9.2	11.6
WHS25	0	0	0	0	0	0	15	14.7	9.5

5

SIMULATION MODELING: STEEL LADLE LOGISTICS

On the basis of literature findings presented in Chapter 2, outlined research methodology in Chapter 3, and the conceptual model described in Chapter 4, a discrete event simulation model of steel ladle logistics has been developed. In fact, the SimPy library adopted for building the simulation model has promising abilities as it accurately replicated the real-time situations, as described in the conceptual model. The current chapter explains the integration approach of simulation & optimization model in Section 5.1, modelling objectives in Section 5.2, phases in ladle logistical cycle in Section 4.2, simulation model development process in Section 5.3.

5.1. INTEGRATION OF MODELS

One of the primary outcomes of this study is to demonstrate the evaluation methodology by integrating the developed simulation model with an optimization model addressing steel ladle logistics dispatching problem. In general, a simulation model will be developed to virtually simulate and analyse the behaviour of entities in a physical system. Based on the configurations of simulation model, it would be capable of dynamically dispatching entities of system based on dispatching rules. But in this research study, the ability to dynamically dispatch ladles for the charges of a given production scenario is not required. It is because, the functional requirement of simulation model is to simulate and evaluate the behaviour of ladle dispatching decisions generated by optimization model in the real-world behavior. As a result, solutions proposed by the optimization model serves as a input for simulation model. Borodin et al. [14] emphasized this kind of integration as ***'Simulation encapsulated into optimization'***.

Ruela et al. [72] has proposed an optimization model to address the ladle dispatching problem by adopting the use-case of OSF2 at Tata Steel, Ijmuiden. This optimization model chosen as subject for evaluation requires production scenarios[1] as an input for model execution. Given the production scenarios, the optimization model tries to determine the optimal ladle deployments. As a result, the primary output of optimization model would be ladle assignments and their dispatching decisions for each charge of a given production scenario. The optimization model also generates the tilting and reheating stand assignments for each charge of production scenario as outputs. But these assignments might not be possible to be followed by the DES model, as their availability becomes uncertain due to the stochastic process parameters. For instance, as the transportation duration from casting to tilting stands is stochastic in DES model (which are relatively higher than optimization model), the tilting stand may not be available by the time ladle reaches location.

As the ladle assignments are fixed for each charge in a production scenario, the simulator expects to dispatch the ladle to subsequent charge at specified time. As a result, available time for the empty ladle operations are fixed, i.e., simulator cannot elapse more time than available to complete the operations. Therefore, evaluating the ladle dispatching decisions by DES model with stochastic parameters for empty ladle operations makes the process efficient. Consequently, the dispatching decisions generated by the optimization model, serves as an integration parameter between the models. Assuming these decisions along with production scenarios as the input, DES model simulates them in more realistic logistics of steel plant.

5.2. MODELLING OBJECTIVES

The principle objective of this research is to evaluate the ladle dispatching decisions generated by the optimization model in terms of: *the feasibility of the production schedules, the thermal balance of ladles throughout operations, and sustainability indicators of schedules.* So, it is also important to be aware of the constraints and objectives underlying the selected optimization model, as they serve as the parameters of evaluation. Typically, the optimization model assigns a ladle (by tracking the thermal state of ladles) per charge within the production scenario by adhering to the following optimization objectives:

- To utilize as less ladles as possible.
- To minimize reheating times of ladles.
- To minimize idle times of ladles.

The model aims to address these critical objectives for energy-efficient ladle management within a production scenario. In addition to the objectives, the optimization model also has a constraint to dispatch the ladle to a charge only if it has a refractory temperature greater than a minimum safety value.[2] According to the methodology, the DES model is responsible to check the feasibility of respecting constraints and ability to reach optimization objectives when executed in real world dynamics. Therefore, these objectives and constraints serve as a direction for evaluating results after execution of the models.

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[1] A Production Scenario is a schedule of charges anticipated to complete for a given day at steel-plant.

[2] In order to gain more detailed insights into the referred optimization model, please have a look at Ruela et al. [72].

5.3. MODEL DEVELOPMENT

In order to evaluate modelling objectives and constraints DES model was systematically developed in different phases. The DES model has three main components that realizes the real world behavior of steel ladle logistics in simulated environment.

5.3.1. STUDY ASSUMPTIONS

While developing the simulation model, few assumptions are made, tailored to the scope of research study in order to overcome convolution and maintain coherence with the optimization model selected as the subject for evaluation:

- All the ladles are assumed to be new and at 700°C corresponding to its initial charge within a production scenario. This implies that all ladles assigned to a production scenario have new undergone refractory relining and preheating to reach 700°C.
- Owing to the complexity and feasibility of modelling phase, the dynamic location and tracking of cranes at any given time in steel plant are not included in the model and assumed to be available to pick the ladle when ever required.
- A ladle is assumed to be reheated near to tapping. That means ladle would be left idle after maintenance and only reheated based on transport duration and initiation of assigned subsequent charge.
- In the situations where reheating the ladle to minimum tapping temperature is not feasible, the simulator bypasses the reheating phase and assumes the ladle to stay idle at tilting stand until subsequent charge.

5.3.2. RESOURCES IN A STORE

Among all the resources (Figure 4.2) required for the steel-making process, ***ladles; reheating stands; and tilting stands*** requires vigilant monitoring throughout the simulation of a production scenario. The remaining resources, namely *"converters, casters"* don't require such monitoring as their assignments are already provided in production scenarios data. So, ladles; reheating stands and tilting stands are defined as a pool of resources: ***ladlePool, reheatingStandPool & tiltingStandPool.*** These resource pools are generated based on the in-built feature provided by SimPy package, *store.*[3]

In order to enhance and specify supplementary monitoring functionalities to resource pools, a Python class *MyResourcePool()* was defined. This class encapsulates multiple User Defined Function (UDF) aimed at creating a ResourePool object, deploying, monitoring, and releasing a resource. The schematic representation of classes and methods essential for the operation is illustrated in Figure 5.1.

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[3] SimPy Resource Type Store: `https://simpy.readthedocs.io/en/3.0/api_reference/simpy.resources.store.html`

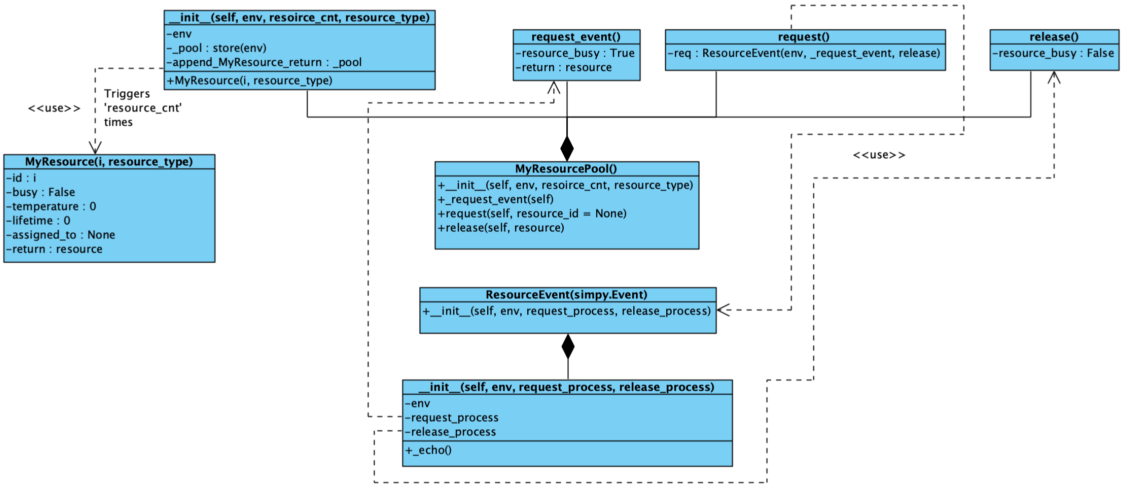

Figure 5.1: Creation and Management of Resources in DES model

While creating an object of MyResourcePool, the constructor receives two parameters to create the resource pool: *resource_count, resource_type*. The constructor initially creates a simpy.store() in the simulation environment. Subsequently, it iteratively appends *'resource_count'* number of resources to the 'store' instance. Upon each resource creation, it defines the following monitoring parameters: *id, busy, assigned_to*. Notably, for the case of *'ladlePool'* instance, it assigns the following additional parameters: *temperature, lifetime*. The *'id'* parameter of each resource is unique and dependent on 'resource_type' such that it acts as an resource identifier.

As illustrated in Figure 5.2, whenever an event requires a resource out of a *'MyResourcePool()'* instance, a request would be opened through the *'request()'* method of the *'MyResourcePool()'*. This request returns a resource from the resource pool if any of the resources are available in the pool. If all the resources in the resource pool are busy, the request remains open till one of them becomes available. Whenever a resource is deployed from the pool, it comes out of *store* and the *'request_event()'* methods stay responsible for monitoring the resource. The main operation is to turn the *'busy'* parameter of resource as *True* and record deployment time. Upon releasing the resource from usage, the *'busy'* parameter turns to *False* and *resource_usage* duration is be computed. The released resource goes back into their respective *store*.

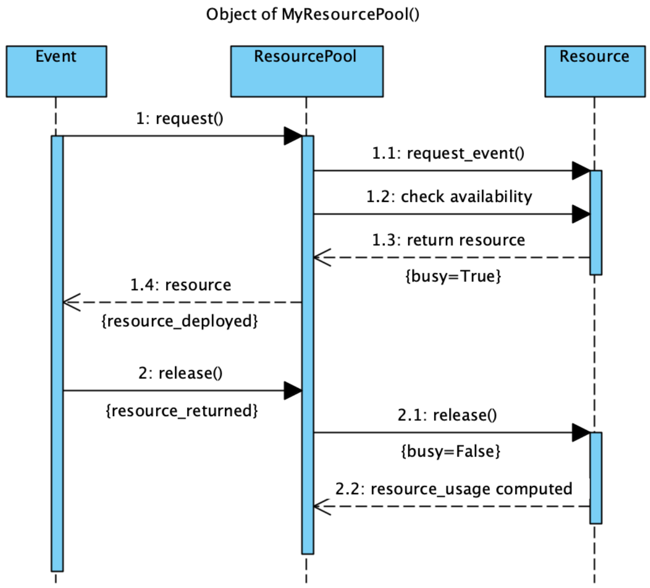

Figure 5.2: Process of requesting and releasing of a resource in DES model

5.3.3. TRANSPORT DURATION

As illustrated in Figure 4.5, a steel ladle travels through various locations in the OSF2 plant to accomplish steel-making operations. So, it is inevitable for the DES model to calculate the transport duration between the locations to make them realistic. Consequently, efforts were undertaken to determine the location coordinates of each steel-making installation within the OSF2 plant.

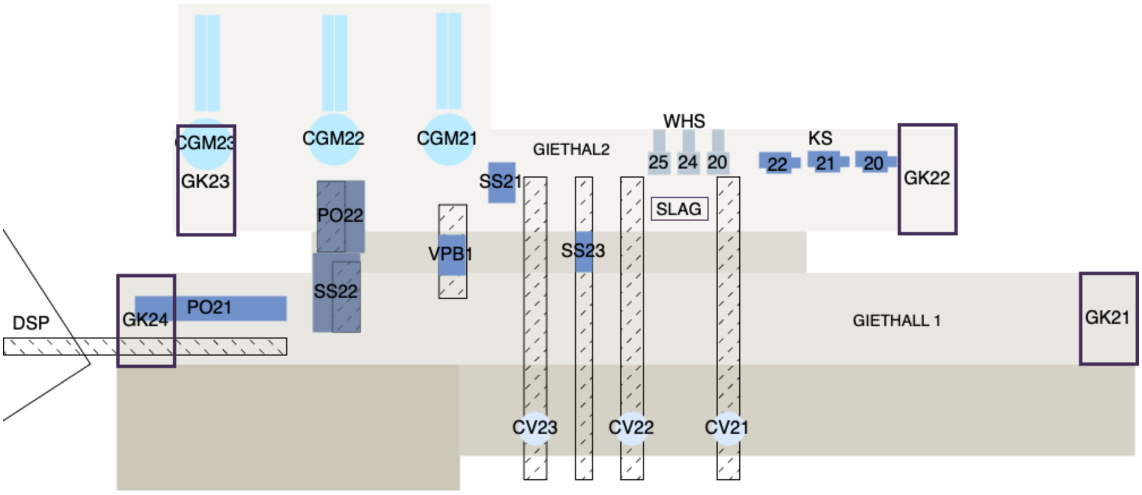

Figure 5.3: Simplified OSF2 Steel Plant Layout

In order to decrease the complexity to the simulation model, few simplifications were made to the placements of heating stands and tilting stands. In contrast to the original plant layout (Figure 4.1), all the tilting stands and heating stands are assumed to be installed in *Casting Bay 2* (Giethal2). The simplified version of plant layout, considered in the present study is illustrated in Figure 5.3. Despite the simplification, the simulation model is still valid, because the validation is in between optimization model and simulation model, but not between simulation model and real-world installations. Nevertheless, the simulation model computes realistic transport durations in contract with optimization model making it more realistic. The reliability and effects of the assumption was also verified by consulting an stakeholder at TSNL. Figure 5.4 depicts the locations of various steel-making installations on a Cartesian Plane when sighted through the top view.

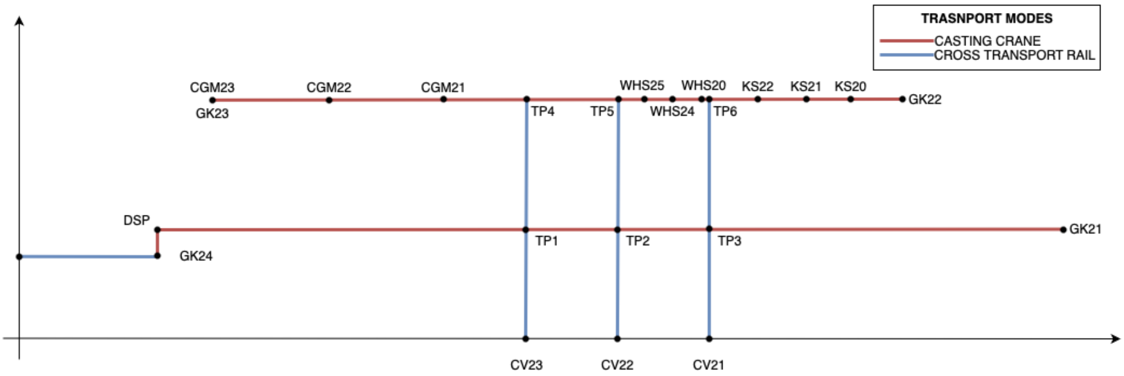

Figure 5.4: OSF2 Steel Plant Layout as a Cartesian Plane

In accordance with the objectives and constraints of the optimization model, as well as the inherent constraints of steel-making (Figure 4.5), three transportation duration's are identified to be crucial: *transport_maintenance, transport_reheating, transport_tapping*. These transportation duration's significantly influence the thermal state of the ladle, particularly impacting the reheating duration before tapping (in-detail explanation in Section 5.3.4).

The transport duration from the converter location to secondary metallurgy and subsequently to the casting location is excluded from the scope of this study. As depicted in Figure 4.5, the Secondary Metallurgical phase encompasses numerous operations that are complex to model. As a result, the operations between tapping and casting are treated as a black box in DES model in coherence with optimization model proposed by Ruela et al. [72].

Based on transport routes briefed in Section 4.4.2, a specific transport path for each operation was identified, by incorporating a few turning points: *tapping_path, direct_tapping_path* (if reheating is skipped after maintenance), *maintenance_path_cgm* (for ladle at CGM), *maintenance_path_dsp* (for ladle at DSP), *reheating_path*. As depicted in Figure 5.4, based on the origin and final location of transport, the algorithm picks the path and calculates the theoretical travel time between them, based on the distance to be travelled by crane and cross transport against their respective velocities.

$$t_{theoretical} = \frac{d_{crane}}{v_{crane}} + \frac{v_{crosstransport}}{s_{crosstransport}}$$

In order to enhance the realism of the *travel_duration, theoretical_travel_duration* needs to be combined with the duration an transport equipment needs to reach the ladle location. This demands the DES model to dynamically monitor the transport equipment's. Due to the time constraints of research study and complexity of modelling transport equipment's, their dynamic monitoring has not been feasible. In order to overcome the limitation, for each transport event, a stochastic waiting time (briefed in Section 4.4.2 and Table 4.1) was incorporated to *theoretical_travel_duration*.

$$t_{travel} = t_{theoretical} + t_{waiting}$$

5.3.4. REHEATING DURATION

Among the objectives of optimization model proposed by Ruela et al. [72], optimizing the reheating duration of ladles was observed to possess higher priority. Consequently, it is necessary to make the reheating event as realistic as possible in the DES model to check their impact on system performance. Fulfilling this requirement necessitates the thermal tracking of a ladle throughout its operational cycle. As a result, whenever a steel ladle undergoes a stage transition (Figure 4.3) respective thermal state was computed. This computation relies on the *ladle's initial temperature before the stage, duration of the stage, and lifetime of the ladle.* These computations are generated by adopting an thermal model developed and being used by TSNL [4]

As the outputs of optimization model serves as input for the simulator, it is pre-informed about the available time before dispatching the ladle to the subsequent charge. Within the *'available_time'*, the simulator initially reserves the time for transporting the ladle from the maintenance location to the reheating area and subsequently to the converter location, as it already knows the converter location of subsequent charge. The residual duration represents the available time for reheating.

As underlying assumption of Ruela et al. [72] and current study is to reheat the ladle close to tapping, it would be left idle until it requires reheating. So, an UDF 'estimate_heating_duration()' was defined to estimate the idle duration before reheating and reheating duration. It receives the following parameters for estimations: *transport to reheating, transport to tapping, temperature at maintenance end, expected temperature for tapping, ladle lifetime.* The method has an iterator, that iterates over *'available time'*.

The iterator variable *'reheating duration'* serves as the heating duration of the iteration. The difference of *'available time'* and *'reheating duration'* represents the *'idle duration before reheating'*. With each iteration, the simulator computes the thermal state of the ladle, considering transport duration, idle duration, and reheating duration. As the transport duration after reheating is an *stage:EMPTY* operation, the ladle experiences a drop in temperature. Therefore, the simulator reheats the ladle to a temperature above the expected minimum tapping temperature, such that it reaches the anticipated thermal state as it reaches the converter.

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[4] For confidentiality and sensitivity reasons, details regarding the thermal model of TSNL are not disclosed in the thesis. A similar thermal model was adopted by Ruela et al. [72] in their study to develop the optimization model for ladle logistics. In order to gain more insights into thermal model, please refer to that research article.

The iterator stops when the simulator identifies the ladle temperature to be more than minimum tapping temperature and returns the *'reheating duration'* and *'idle duration before reheating'* of the iteration. It is noteworthy that, the DES model skips reheating phase and assumes ladle in idle state succeeding maintenance phase in two scenarios:

- If the iterator fails to find an combination of *'reheating duration'* and *'idle duration before reheating'* within *'available_time'* to reach minimum tapping temperature.
- By the moment an reheating stand becomes available and assigned to a charge, if the available time for reheating fall short compared to the estimated *'reheating_duration'*.

It is because, the main objective of DES model is to validate if the ladle reaches anticipated tapping temperature by following the ladle dispatching schedules generated by an optimization model. Therefore, it was assumed that, if the simulator cannot reach minimum tapping temperature for a ladle, it would bypass the phase and wait idle till it moves for subsequent charge.

5.4. SIMULATION GENERATOR

In the previous section, the design approach and functional characteristics of all the essential components of the simulation model are described. Following that, the subsequent phase was to systematically integrate the components, ultimately leading to the development of a simulation generator function. Prior to the integration of these components into the generator function, each one of them was tested to verify the expected behavior.

In order to carry out simulation of the production scenarios, the foremost task entails defining a simulation environment as *'env = Simpy.Environment()'*. This environment is responsible for holding the created resource pools, triggering generator functions, and remains operational with a single simulator clock until all the charges within the production scenario are simulated. Subsequently, *ladlePool*; *reheatingStandPool*; *tiltingStandPool* are created by defining object instances of class *'MyResourcePool()'*. The number of resources created in resource pools are (as illustrated in Figure 5.4):

- ***ladlePool:*** Optimization Model results specifies the number of ladles required for a given production scenario.
- ***reheatingStandPool:*** OSF2 has three reheating stands (WHS) (Figure 4.1)
- ***tiltingStandPool:*** OSF2 has three tilting stands (KS) (Figure 4.1)

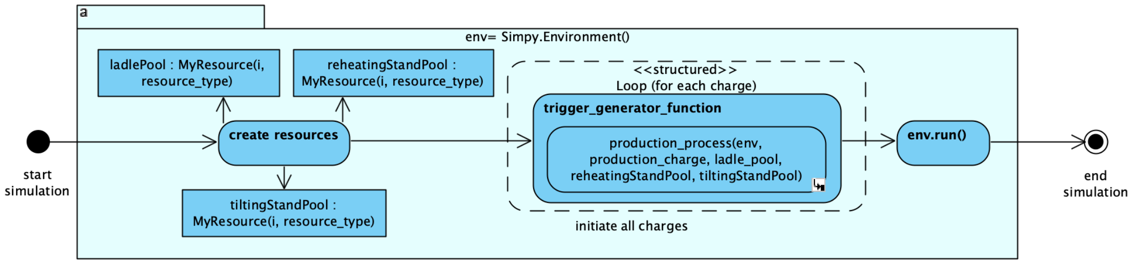

Figure 5.5: Overview of resource creation & process simulation

For each charge within a production scenario, the simulator triggers a generator function by passing all resource pools and numerous charge parameters as arguments [5]. This generator function is responsible for simulating all the discrete events of the respective charge by encompassing all the simulation components.

The simulation environment's (*env*) generator function works as follows. The simulator initially checks the *'tapping start'* time of the charge. Technically, this timestamp is considered to be the starting point (*startCharge*) of simulation. After the simulator *timeout()* the environment clock to *'tapping start'* time, it picks the ladle specified by optimization model for the respective charge, from the *'ladlePool'*.

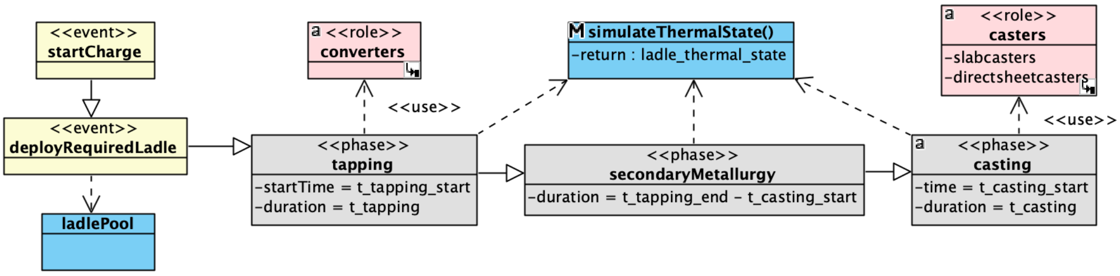

Figure 5.6: Modelled Discrete Events of Tapping to Casting Phases

The steel-making simulation begins following the deployment of a *ladle* out of *ladlePool*, as illustrated in Figure 5.6. At the specified *'tapping location'* and *'tapping start'* time, ladle completes tapping the charge within *'8.5 minutes'*. Consequently, the simulator times out the environment by that duration. As per the assumptions of the study, the time interval between *'tapping end'* and *'casting start'* is considered as the secondary metallurgical phase. As a result, the simulator times out the environment by that duration as well. Similar to tapping phase, at specified *'casting location'* and *'casting start'* time, the simulator times out the environment by *'casting duration'*. At the end of each phase, the simulator was deemed to compute the thermal state of ladle. The timings and duration of all simulated operations up to the current point are predefined in input data *'production scenarios'*. The residual time interval until the currently deployed ladle taps the next charge would be utilized for accomplishing further preparatory

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[5] Detailed explanation of charge parameters is provided in Section 6.1.1 and Table 6.1.

phases (*maintenance* & *reheating*).

As specified in Figure 5.7, the simulator initiates the maintenance phase at the time *'casting end'*. Initially the simulator opens an request to *'tiltingStandPool'* utilizing the *'request()'* method. If none of the tilting stands are accessible at this juncture, the request remains open till one of them becomes accessible. In this situation, it is assumed that the ladle remains on the ladle turret of caster, until a tilting stand is available. Subsequently, based on the assigned tilting stand for the maintenance operation, the simulator calculates the transport duration from the casting location to the maintenance location employing *'transport_between_locations()'* method and times out the environment by this duration. As explained in Section 4.3.5, the maintenance duration would be sampled from the distributions derived from historical data and Reinders [70]. Consequently, the simulator times out the environment by that duration.

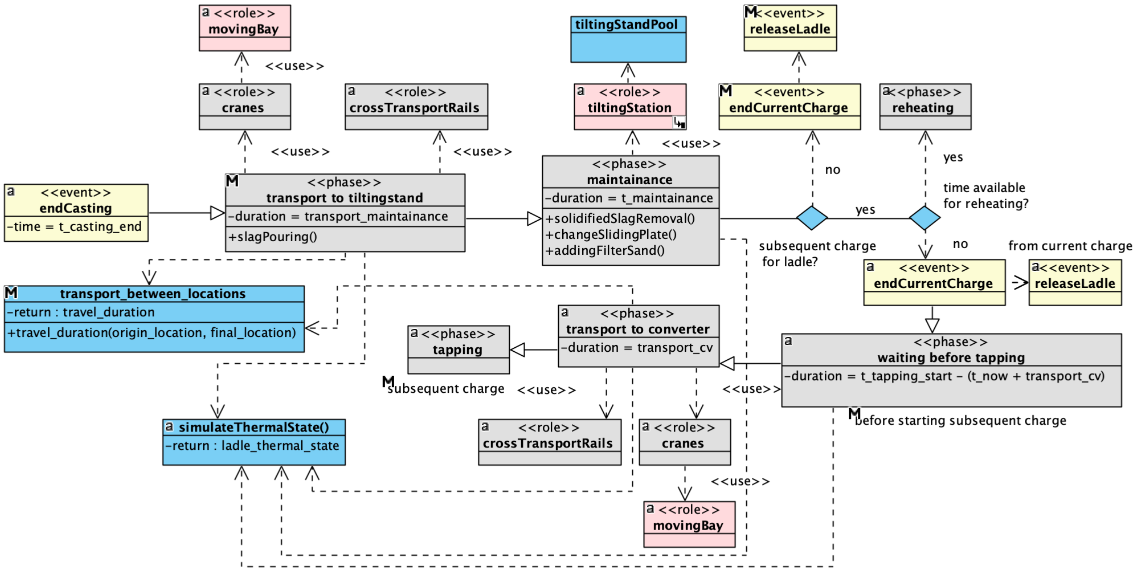

Figure 5.7: Modelled Discrete Events of Maintenance Phase

As the simulator accomplishes the maintenance phase of the steel-making cycle (Figure 4.5), it checks two decisive conditions prior to advancing to the reheating phase, as depicted in Figure 5.7. The first condition checks whether the ladle currently in use possesses a subsequent charge within production scenario data anticipated in the future. If no subsequent charge is scheduled, the simulator skips the reheating phase and releases the ladle from the operation, marking this point in time as the *'endCurrentCharge'* event. Conversely, if the subsequent charge is scheduled, the simulator inspects if the time is available for reheating based on *'tapping_start'* and *'tapping_location'* of subsequent charge:

$$t_{available} = t_{tapping\_start} - (t_{now} + t_{transport\_cv})$$

At this moment, while calculating available time, the simulator doesn't yet have the information regarding the feasibility of reheating and the precise location, if feasible. As a result, the simulator considers the maximum duration a ladle takes from any of the reheating stands to specified *tapping location*. Subsequently, if the simulator finds *available time* > *0*, it initiates the reheating phase. Otherwise, it omits the reheating and remains idle until it starts moving towards *'tapping location'* of subsequent charge.

Upon the simulator's conclusion to carry out the reheating of the ladle after verifying the feasibility, additional computations and assessments are required before commencing the reheating phase. As illustrated in Figure 5.8 initially the simulator adopts the *'estimate_heating_duration()'* method described in Section 5.3.4 for estimating the idle duration (*waiting_before_reheating*) and reheating duration (*t_reheating*). Consequently, the simulator times out the environment by *'idle_duration'*. At this point in time, the simulator opens a request to *'reheatingStandPool'*, through *'request()'* method of *'MyResourcePool()'*. This request remains active until the simulator's environment coincides with the time the ladle needs to start moving for tapping subsequent charge:

$$t_{start\_movement} = t_{tapping\_start} - t_{transport\_cv}$$

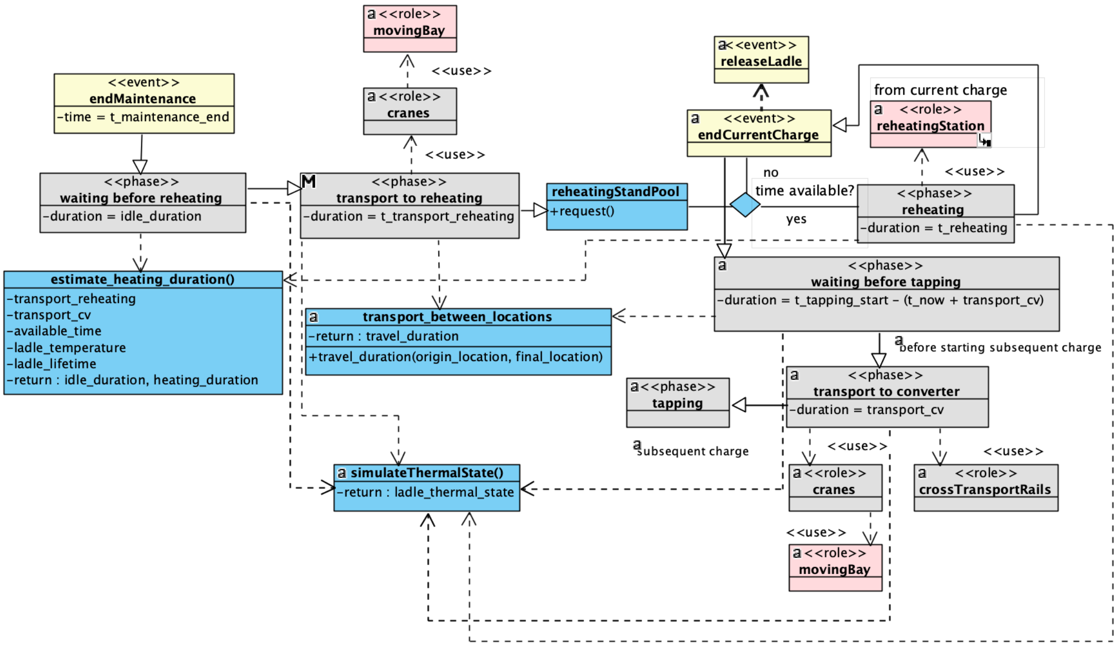

Figure 5.8: Modelled Discrete Events of Reheating Phase

As the ladle is still at the maintenance location while requesting the reheating stand, *'transport_cv'* in the above equation represents the transport duration from the maintenance location to the tapping location of the subsequent charge. If the simulator succeeds in deploying a reheating stand based on the condition, the ladle moves to that location. At this juncture, it becomes necessary to revisit the *'reheating duration'* returned by *'estimate_heating_duration()'* method. It is imperative due to the possibility that the simulator may elapse a waiting period to the environment if none of the reheating stands are available upon request. Consequently, if it is not possible to reheat the ladle to anticipated duration, the simulator skips reheating adhering to the underlying assumptions. If it is feasible, the simulator environment times out *‘t_reheating’* duration, and marks the thermal state of the ladle and starts moving towards the converter location for tapping the subsequent charge.

Figure 5.5 illustrates that, for each charge in the production scenario, the simulator initializes an instance of generator function *‘production_process()’* utilizing the function *‘env.process()’*. These instances are created but remain dormant and not yet executed. When the simulation environment encounters *‘env.run()’* in the algorithm, it carries out actual simulation.

6

EXPERIMENTAL SET-UP

6.1. GENERATING PRODUCTION SCENARIOS

As delineated in the preceding chapters, the DES model was developed based on the system analysis and conceptual model of OSF2 plant at TSNL. According to the research methodology, illustrated in Figure 3.2, the subsequent task following simulation modeling entails experimental validation for the intended application. The principal objective of the research study is to construct an DES model aimed at evaluating the ladle dispatching decisions generated by an optimization model. Essential to this process, the optimization model necessitates production scenarios as fundamental input data to generate the dispatching decisions.

A production scenario is a list of numerous charges anticipated to be carried out at a steel plant, constrained by the start time of tapping and casting operations. The optimization model, proposed by Ruela et al. [72], relies on essential data about tapping time, casting time, and casting duration of each charge as its input. It is because the optimization model iteratively converges towards generating an optimal & energy-efficient ladle dispatching schedule, to fulfill optimization objectives and constraints, which include but are not limited to the aforementioned parameters. As a result, it is imperative to derive the production scenarios for generating optimized ladle schedules and then evaluate its decisions by DES model.

6.1.1. DATA COLLECTION & PROCESSING

In order to establish reliable production scenarios for the experimentation, historical production data of TSNL was utilized. It is because, the historical data possesses the precise *'date-time'* values for tapping and casting operations, ensuring accuracy and reliability in the derived scenarios. The operators working in the plant and ladle tracking systems assists in recording the start and end timestamp of each operation in the steel-making cycle. Therefore, the tables holding required historical data are identified and acquired from an stakeholder at TSNL for the time period between January 2024 and March 2024[1]. Several filters and data processing steps are applied to the acquired data for generating the required production scenarios in the form of interest

According to the insights by an stakeholder and data catalog of TSNL, relevant attributes from all the tables are identified. Across all the tables, *'charge_id'* was found to be the common attribute and unique identifier. Subsequent to this scrutinization, a systematic data processing procedure was implemented for each day within the selected time frame, i.e., from *01/01/2024* to *31/03/2024*.

Initially, charges from all the tables observed to be occurring within a specified day, are filtered using start time of tapping. Typically, a casting sequence in steel plant constitutes a minimum of two charges. Consequently, the casting sequences are utilized to filter the sequences with only more than two charges. Following the exclusion of unreliable casting sequences, all tables are joined into a unified entity as *'production_scenario'* by adopting an common attribute.

The resultant table *'production_scenario'* was further processed to order the charges based on end time of casting[2]. The final stage in data processing involved converting the attributes of datatype *'DateTime'* into *'time in minutes'*. For every production scenario, the earliest *'tapping_start'* timestamp was designated as the origin, i.e., point in time as *'0.0'*. Subsequently, all other *datetime* values in the table are converted to minutes by relating them to the initial *'tapping_start'* timestamp. An overview of attributes present in the generated production scenarios dataset is described in Table 6.1.

Table 6.1: Overview of generated Production Scenarios Dataset

Attribute	**Datatype**	**Description**
scenario	Integer	Identifier to recognize a scenario in dataset
name	string	Specifies the number of charges, minimum required casters and converters for the scenario
cast	Integer	Indicates if charge is casting at CGM or DSP
charge	Integer	Sequence id of a charge in scenario
tapping_start	Float	Start point (in time) of tapping the charge in minutes
casting_end	Float	End point (in time) of casting the charge in minutes
casting_duration	Float	Time interval to cast the charge
machine_tapping	Integer	Converter identifier (CV)
machine_casting	Integer	Casting Machine identifier (CGM / DSP)

The production scenarios were generated in two distinct batches, following the data processing methodology outlined in Section 6.1.1. One batch encompasses the charges solely related

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[1] Owing to the sensitivity and confidentiality of the data utilized for research, detailed insights regarding tables are not disclosed in the Thesis.

[2] Detained explanation on considering end time of casting for sorting the charges within a production scenario can be found in Ruela et al. [72].

to CGM, while the other batch incorporates charges related to both and CGM & DSP. This partitioning aimed to assess the optimization model's capability to generate potentially optimal ladle schedules for shorter and longer production scenarios with the predefined optimization time frame. As a result, a total of 182 production scenarios were generated to execute both optimization and DES models.

6.2. EXPERIMENTATION APPROACH

The experimentation comprised two phases. In the initial phase, the optimization model was executed in Python 3.10 along with Pyomo 6.5.0 modeling language [38]. The experiments were executed by adopting Gurobi 10.0.0 [35] on a Linux Server of 128-core AMD EPYC 7702P with 256GB RAM configuration. Following a methodology akin to that described in Ruela et al. [72], the optimization model aimed to generate schedules by optimizing the heating and idle times of a ladle with their objective weights being $\lambda_1 = 2$ and $\lambda_2 = 1$ respectively, ensuring that the refractory temperature of the ladle at the time of tapping is a minimum of 700°C. All the ladles when assigned to its corresponding first charge is assumed to be new (*lifetime:0*) and at temperature equal to 700°C. The solver was constrained to terminate after a maximum of 10000 seconds or upon achieving a 0.1% optimality gap.

Upon completion of the optimization model's execution across 182 production scenarios, the results are stored in a database for further processing. The solver outputs are always stored and can be used to identify the final optimization status and optimality gap, even for the failed scenarios. Essential among these results are the ladle assignments for each charge within all production scenarios, as they are a prerequisite for advancing to the subsequent phase of experimentation.

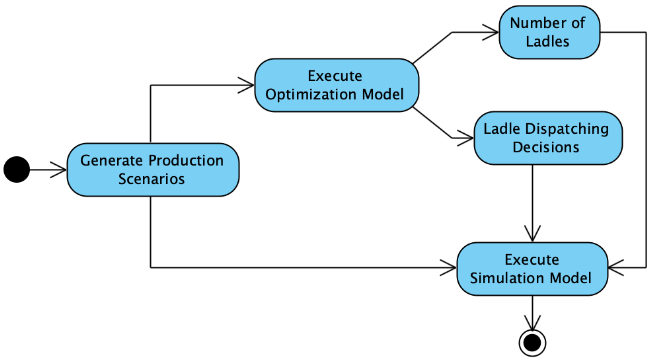

Figure 6.1: Experimental Approach followed in the research study

Consequently, from the database holding the results of the optimization model, the ladle assignments of each production scenario are retrieved. These assignments are merged to the earlier generated production scenarios based on the shared attributes *scenario & charge*. As a result, the production scenarios serving as the input data for the simulation model now possess two additional attributes: *'ladle'* and *'ladle_lifetime'*.

The attribute *'ladle'* refers to the ladle assigned to a particular charge within a production scenario, while *'ladle_lifetime'* represents the count of the steel-making cycle accomplished by a ladle. The *ladle_lifetime* initially starts at *0* while accomplishing its first assigned charge in a production scenario. As the ladle progresses through a single cycle of steel-making (Figure 4.5), the lifetime increments by one. This parameter plays a crucial role in estimating the thermal state of the ladle at any given operation within the steel-making cycle.

Table 6.2: Overview of Fixed Process Durations of Optimization Model [72]

Attribute	**Duration (mins)**
Transport duration from Casters to Tilting Stands	10
Transport duration from Tilting Stands to Reheating Stands	10
Transport duration from Reheating Stands to Converters	15
Maintenance Duration	25

As specified by Ruela et al. [72], Table 6.2 reports the deterministic (fixed) process durations, considered by the proposed optimization model. In contrast, the DES model developed in this research study, endeavors to make them realistic to match their stochastic behavior in real time. As specified in Section 4.3.5, the DES model considers the maintenance duration as a uniform distribution varying between 20 to 25 minutes. It is because, the insights from analysis of historical database and Reinders [70] revealed that the every outcome within the above range is equally likely to happen. It was also found that the maintenance can be completed lower than 20 minutes and greater than 25 minutes, but the probability of occurrence was found to be relatively low.

In the context of DES model, the reheating durations for each charge are computed by adopting the *'Reheating Module'* described in Section 5.3.4. This module, iterates over the available time before the ladle starts moving to subsequent charge. For each iteration, it increments the *'reheating duration'* by *'5 minutes'*. It is found through various experiments that, if the reheating duration is incremented around 2 minutes, there are situations where the ladle is reheated for two minutes and started moving for tapping subsequent charge, which is unrealistic to happen in real-time. When it is incremented through 10 minutes, chances to reheat the ladle was deprecated more often, making it unfair for the validation and comparison. As a result, it was assumed to increment the reheating duration by *'5 minutes'* for each iteration.

Following the approach briefed in Section 5.3.3 transportation durations between different steel-making installations are computed considering the realistic distances between them and sampled waiting times. As a result, it makes clear that DES model yields different outcomes each time the same production scenario is simulated, due to the stochastic behavior of maintenance and transport durations. As described in Section 5.3.4, these durations are important in the research study because they execute realistic simulations.

In the context of statistics and machine learning, the sampling distribution tends to closely approximate a normal distribution when the sample size is at least 30 [90]. Consequently, to ensure valid & justifiable comparisons between the optimization and simulation model results, it was determined to execute the simulation model 30 times for each production scenario.

6.3. EXPERIMENTATION RESULTS: OUTPUT

As the optimization and simulation model are executed, the output data is collected and stored for the result analysis. Apart from the ladle assignments data for each charge within a production scenario, optimization model also stores several other outputs in the results database. Among them, two important tables required for the feasibility and comparative analysis are chosen. These tables hold the information related to the ladle assignments and process durations.

Table 6.3 provides a comprehensive overview of resource allocations pertaining to particular charges within a production scenario. Specifically, it elucidates the ladle assigned to each charge, along with the ladle's lifetime, initial and final refractory temperatures. Additionally, it indicates the respective tilting stand and reheating stand assigned for maintenance and reheating operations of the charge.

Table 6.3: Overview of Optimization result values Dataset

Attribute	**Description**
scenario	Sequence Identifier of a production scenario
charge	Identifier of a charge with in a production scenario
ladle	Identifier of a ladle assigned to corresponding charge
ladle_lifetime	Lifetime of a ladle at corresponding charge
ladle_initial_temperature	Refractory Temperature of ladle before tapping operation
tiling_stand	Identifier of a tilting stand where maintenance operation of charge is accomplished
reheating_stand	Identifier of a reheating stand if ladle is reheated during corresponding charge
ladle_final_temperature	Refractory Temperature of ladle at the end of charge

Table 6.4 provides an overview of empty stage durations estimated by the optimization model for each charge within a production scenario. The attribute *'empty_duration'* indicates the time interval during which the ladle undergoes empty ladle operations, typically from the end of casting the current charge to the commencement of tapping the subsequent charge. Conversely, the attribute *'idle_duration'* denotes the cumulative time intervals during which a ladle remains idle when it is empty. A detailed explanation regarding idle duration is presented in Section 6.4. Similarly, *'reheating_duration'* indicates the interval of time a ladle undergoes reheating before being dispatched to subsequent charge.

In the case of DES model, data handlers are incorporated into the simulation script to capture

Table 6.4: Overview of Optimization result: Operational Timings Dataset

Attribute	Description
scenario	Sequence Identifier of a production scenario
charge	Identifier of a charge with in a production scenario
ladle	Identifier of a ladle assigned to corresponding charge
empty_duration	Interval of Time a Ladle is empty
reheating_duration	Interval of Time a Ladle is reheated during the corresponding charge
idle_duration	Interval of Time a Ladle is idle between the operations in Steel-making cycle

the essential time points from the environment's clock. These handlers are tasked with recording the commencement and conclusion of steel-making phases and computed transport durations between the OSF2 installations of each charge within a production scenario. It also stores the computed thermal state of a ladle at the beginning and end of the charge. The overview of DES model results dataset is presented in the Table 6.5. All time related parameters in Table 6.5 are related to the outputs from simulation environment.

Table 6.5: Overview of Simulation Results Dataset

Attribute	**Description**
scenario	Sequence Identifier of a production scenario
charge	Identifier of a charge with in a production scenario
ladle	Identifier of a ladle assigned to corresponding charge
ladle_lifetime	Lifetime of a ladle at corresponding charge
ladle_initial_temperature	Refractory Temperature of ladle before tapping operation
tapping_start	Point of time when tapping is initiated
casting_end	Point of time when casting is accomplished
sm_duration	Calculated internal of time for secondary metallurgy of corresponding charge
transport_maintenance	Computed interval of time for movement of ladle from casting location to maintenance location
tilting_stand	Assigned tilting stand for maintenance operations
maintenance_start	Point of time when maintenance is initiated
maintenance_duration	Sampled maintenance duration for the corresponding charge
waiting_before_reheating	Interval of time a ladle waits after maintenance for reheating
transport_reheating	Computed interval of time for movement of ladle from maintenance location to reheating location
reheating_start	Point of time when reheating is initiated
reheating_duration	Estimated reheating duration of ladle to reach intended tapping temperature, i.e., 700°C
idle_after_reheating	Interval of time a ladle remains idle after reheating and before moving to tapping next charge
transport_cv	Computed interval of time for movement of ladle to tapping location of subsequent charge
ladle_final_temperature	Refractory Temperature of ladle at the end of charge
end_time_charge	Point of time the charges is considered completed

The experimental results data from both the models are further processed and analysed to evaluate the ladle dispatching decisions generated by the optimization model.

6.4. EVALUATION METHODOLOGY

As emphasized in the Problem Definition (Section 1.3), the DES model was developed and executed to conduct a feasibility analysis of the ladle dispatching schedules generated by the optimization model. Compared to the optimization model proposed by Ruela et al. [72], the DES model replicates the operational dynamics of steel-making at OSF2, incorporating the realistic estimations of emptied ladle operation durations and transportation. Consequently, the DES model was employed to verify the feasibility of reaching steel-making and optimization constraints by following the optimization objectives.

These objectives of the optimization model are observed to be interdependent to make the ladle dispatching decisions energy efficient. For a ladle, to attain the minimum tapping temperature upon reaching the tapping location, it needs to undergo adequate reheating. Failure to achieve this constraint, may result in safety constraints and increased refractory wear. The optimization model when executed for a given production scenario tries to find a possible ladle dispatching schedule by adhering to these objectives.

As a result, the methodology for evaluating the dispatching decisions of the optimization model is branched into two phases. The initial phase addresses the feasibility analysis of results in meeting the specified constraints and objectives. Subsequently, the second phase entails conducting a comparative analysis of sustainability indicators reported by the optimization model againt estimations generated by DES model.

6.4.1. FEASIBILITY ANALYSIS

The fundamental motivation for the feasibility analysis is to ascertain whether the ladle assigned for a particular charge within a production scenario respects the tapping start times by also satisfying the minimum tapping temperature constraint. Given that the maintenance and transportation durations in the optimization model are fixed [72], the ladle dispatching decisions might be feasible to attain the required thermal state in the context of optimization model. Whereas in the real-world dynamics of steel-making, they might remain uncertain. Consequently, assuming the more realistic logistical parameters, the DES model evaluates if the optimization model outputs are safe to execute in the steel plant, i.e., if a charge fails to attain minimum tapping temperature constraint by respecting tapping start time, it can raise safety concerns in steel plant.

During experimentation, the minimum tapping temperature of a ladle has been fixed at 700°C. Upon convergence of the optimization model to an optimal solution for a given production scenario, it ensures that a ladle would attain the minimum required temperature before it reaches the converter for tapping. Consequently, the average of all the tapping temperatures in the production scenarios would be greater than or equal to 700°C.

In the case of DES model, the simulator picks the ladle specified by the optimization model for a particular charge. While the ladle completes casting and enters empty ladle operations, the simulator calculates maintenance and transportation durations based on sampled values and realistic locations. Consequently, by the time a ladle reaches the reheating phase, the feasibility of reheating becomes uncertain. This uncertainty arises when there is a lack of time to reheat the ladle to a minimum tapping temperature or the unavailability of reheating stations.

During the evaluation of the optimization model, the simulator is constrained to strictly follow the ladle assignments for each charge in a production scenario. As a result, the ladle is dispatched to the specified charge regardless of whether it reaches the necessary thermal state for tapping. It means that, the reheating duration (if it is possible) has an direct influence on the tapping temperature of the ladles.

As specified in Section 6.2, given a production scenario, the DES simulates the ladle behavior in the simulation environment for a total of 30 iterations. As the durations of emptied ladle operations are stochastic, the simulator estimates diverse tapping temperatures for a ladle assigned to a charge for each iteration. Consequently, for each production scenario, a distribution of 30 average tapping temperatures were generated. As a result, the singular average tapping temperature derived from the optimization model was juxtaposed against the distribution to analyse the feasibility to attain minimum tapping temperature.

6.4.2. COMPARATIVE ANALYSIS: SUSTAINABILITY INDICATORS

Apart from the feasibility analysis to respect the constraint of minimum tapping temperature, it is imperative to evaluate how the idle and reheating durations deviate from the optimal solution found by the optimizer. Both of the parameters being the optimization objectives of Ruela et al. [72], they deviate from optimal if realistic maintenance and transportation durations are considered.

The idle duration in the steel-making process constitutes below parameters:

- Waiting duration before a tilting stand is allotted for maintenance operations.
- Waiting duration before a reheating stand is made available for ladle to reheat.
- Duration when a ladle stays idle in tilting stands (if reheating to minimum tapping temperature is not feasible), before it starts moving to tapping location of subsequent charge.

Among these parameters, the first two along with transport duration from reheating stand to converter, has direct influence on the reheating duration and tapping temperature of the ladle. If these durations increase, the available time for reheating and the possibility to find the reheating station when required may be deprecated, resulting in dispatching the ladle to subsequent charge at lower temperature. If a ladle encounters third parameter, then the there is a higher chance that the minimum tapping temperature constraint is voilated.

Therefore, the sum of reheating durations per production scenario as reported by both optimization model and simulation model are compared to justify the insights of the feasibility analysis. As the optimization model reports sum of required reheating duration to attain the required minimum tapping temperature, the simulation model does the same when the reheating is possible. These durations are further linked with the idle durations such that if the idle duration is higher, then reheating is lower and there is a higher risk of not respecting the required tapping temperature.

As emphasized in the literature review (Section 2.3.4), the World Steel Association has delineated a comprehensive set of sustainability indicators for the steel plants (Table 2.3). These indicators are derived in association with the United Nations Sustainable Development goals (SDG), i.e., with each indicator directly contributing to fulfilling a specific United Nations SDG. In alignment with the *'Environmental Performance Principles'* suggested by Worldsteel Association [95], the following indicators are identified based on their relevance to the current research study:

CO_2 EMISSIONS

During the reheating process of a ladle (whenever required in the context of the optimization model and feasible in the context of the simulation model), certain amount of natural gas would be consumed by the heating equipment(WHS). Consequently, based on the duration the burner runs the flame, certain amount of *'CO_2'* will be emitted. The estimation of these emissions (CO_{2est}) was determined by adopting the Burner Flow Rate of TSNL (f) and reheating duration (t_r), as specified by the following equation [7]:

$$CO_{2est}(kg) = f\,(\mathrm{kg/h}) \times t_r\,(\mathrm{h})$$

These estimations of CO_2 emissions addresses the *7^{th} SDG → Affordable & clean energy* and *13^{th} SDG → Climate Action* of United Nations Goals.

STEEL TEMPERATURE LOSSES

During the steel-making process, when the high-temperature molten steel is filled into the ladle during tapping, the steel loses temperature through conduction [27, 87]. Typically, the temperature of molten steel would be between 1500°C to 1700°C and the ladle during tapping would be around 700°C (at least within the context of the study). As a result, when the molten steel is poured into the ladle at a relatively lower thermal state, the heat flows into the ladle's refractory linings [27].

This specific parameter exerts a significant influence on the steel-making process. The temperature losses of molten steel in a steel-making cycle would directly influence the durations of secondary refinement processes. It is a general practice that the temperature of molten steel would be adjusted during secondary metallurgical treatments [33]. As a result, if the steel temperature losses are higher, duration of secondary metallurgical treatments would be higher affecting the production rate and energy consumption of the steel plant [33].

The steel temperature losses would be higher when the ladle is at a lower thermal state while tapping. It is because, heat flows from higher temperature molten steel to the lower temperature ladle refractory walls due to conduction. For any given charge, the *'Steel Temperature Losses'* are computed based on *'refractory_temperature'* at tapping, *'steel_making_duration'* (beginning of tapping to beginning of casting), and *'ladle_volume'*.

Tesselaar et al. [87] emphasised that, tapping molten steel into a lower temperature steel ladle would effect following parameters (corresponding to steel ladles): *Safety, Availability, Reliability, Heat Size, Product Quality and Total Refractory Cost.* Typically, the steel temperature losses are dependent on the tapping temperature of ladles, which is in-turn dependent on the reheating durations. As a result, as the reheating durations, and tapping temperature has a direct influence on temperature losses, system performance was meticulously analysed by connecting them.

According to World Steel Association [95], these sustainability indicators effect the business of a steel plant, either in terms of the revenue or competitiveness among the global steel makers to contribute towards United Nations SDG. Therefore, the comparative analysis of the sustainability indicators on the system performance also provides insights on the business performance upon adopting optimization model in real-time.

7

RESULTS ANALYSIS AND DISCUSSION

7.1. DES MODEL VALIDATION & VERIFICATION

Following the methodology outlined in Section 3.2, developed an DES model (being an prime component for evaluation purpose) adopting the Simulation Methodology proposed by Sargent [73] as its primary research artifact. Owing to the scope, time constraints of the research study, certain components of the simulation methodology were bypasses, by adopting an simpler approach for continuing the process. According to the methodology, in the process of developing a Conceptual Model from the Problem Entity and subsequently a Computerized Model, it needs to undergo *'Conceptual Model Validation'* and *'Computerized Model Verification'*. Sargent [73], mentioned multiple validation techniques that can be adopted throughout the simulation development methodology. The author underscores *Face Validation*, *Structured Walk through* and *Trace* as the primary validation techniques for both *'Conceptual Model Validation'* and *'Computerized Model Verification'*.

Consequently, both the Conceptual Model and Computerized Model underwent validation through *Face Validation, Trace & Structured Walk through*. The conceptual model developed by carrying out a system analysis of the Problem Entity was verified by a stakeholder at TSNL (*Face Validation*) before programming into a computerized model. Similarly, the Computerized model was cross-verified against the conceptual model by *Trace & Structured Walk through*. The model behavior was regularly traced during the development phase to ensure the correctness of logic. Additionally, whenever a stable state of the model is observed, it is reviewed by a stakeholder at TSNL to determine the correctness between the conceptual and computerized model.

Following the successful accomplishment of experimentation, it becomes inevitable to validate and verify the correctness of DES model to ascertain if it behaves as expected. As a result, operation validation was carried out by adopting the strategy of graphical inspection [73].

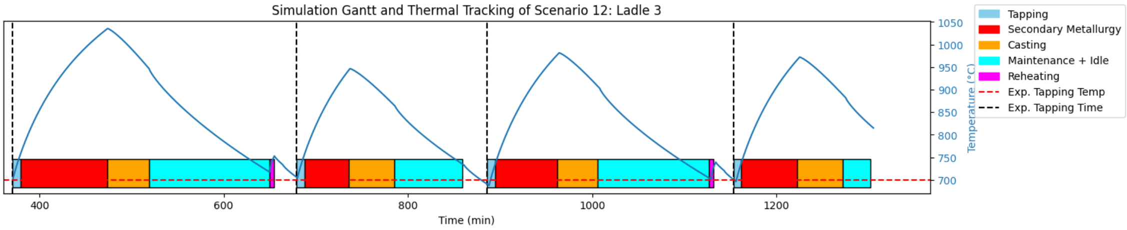

Figure 7.1: DES Model Verification Plot

Therefore, a visualization module was developed to graphically inspect the simulated schedule of any given ladle in a production scenario and its corresponding thermal behavior. Figure 7.1 represents an visualization example plotted for operational validation. During the inspection, following constraints and expected simulator behaviour were verified:

- A ladle need to start the tapping at expected tapping time. It is verified by the coincidence of starting point of gantt representing tapping operation (from simulation model output) with the expected tapping time (from generated production scenario).
- Verifying if the thermal behavior of ladle is as anticipated. The temperature of an ladle increases starting the tapping operation till it initiates casting. Then the temperature decreases until it starts reheating. After completing the reheating operation, while it starts moving towards converter location the temperature of ladle decreases again.
- Check if the ladle is respecting the anticipated thermal state for tapping. If a ladle undergoes reheating before moving towards converter location of subsequent charge, it need to be at 700°C while tapping.

As observed in Figure 7.1, the programmed logic's underlying the DES model are working as expected. The tapping operation of each charge is being initiated at expected tapping time. The ladle's thermal behavior is experiencing an pattern as anticipated. Whenever a ladle is reheated it is respecting the constraint of reaching the minimum tapping temperature as it reaches converter location.

7.2. SELECTION CRITERIA: EXPERIMENTATION RESULTS

During the experimentation of models, 182 production scenarios were generated from the historical production data. These scenarios served as the underlying data for the optimization model for generating an optimal or sub-optimal ladle dispatching schedule. As specified in Section 6.2, an optimization model terminates if it cannot converge to an optimal solution within 10000 seconds for the given production scenario. Consequently, it is considered that the optimization model failed to generate a ladle dispatching schedule for those scenario.

Among 182 production scenarios, the optimization model successfully yielded an optimal solution for 146 scenarios. Notably, among the remaining 36 scenarios where the model failed to yield an optimal solution, 4 were from the first batch of production scenarios with fewer charges, and the remaining 32 arose from the subsequent batch with relatively more charges. This insight underscores the observation that the optimization model requires relatively more time to generate an optimally feasible schedule for scenarios featuring a higher number of charges.

The ladle dispatching decisions generated by the optimization model were simulated for 146 successful scenarios by the DES model. Following the experimentation by DES model and post-processing of results, an additional phase of filtration is carried out to analyze the results only near to true optimal. According to a stakeholder at TSNL, the solutions generated by the optimization model are relevant for evaluation and feasibility analysis only if the Mixed Integer Programming (MIP) gap of the solution is less than 1% as they are near to the true optimal 0%. Consequently, among 146 succeeded scenarios, 24 were identified to possess an MIP gap of less than 1%.

7.3. FEASIBILITY ANALYSIS RESULTS

7.3.1. RESOURCE CONFLICTS

The DES model developed in the current research study possesses certain limitations in replicating the real-world dynamics of OSF2 plant. A specific limitation, concerning the assignments of tilting stands for the maintenance operations was identified.

The simulator operates in a manner such that the tilting stand is released from operation upon completion of maintenance and made available for other ladles. However, despite the simulator assignment of a tilting stand as available, ladle that underwent maintenance at a particular tilting stand remains stationary until it finds a reheating station for heating or starts moving towards the converter location for tapping operation of subsequent charge.

In contrast, as the simulator assumes the tilting stand is available, it gets assigned to another ladle, resulting in conflicts. Given the complexity of ladle placements and transportation within the OSF2 plant, the simulator lacks the capability to resolve this kind of conflict. Figure 7.2 illustrates a simulated production scenario with conflicts in tilting stands (labels on the gantts of the figure represent the corresponding charge executed by the resource).

As observed in Figure 7.2 the assignments of KS2, Ladle 2 (charge 7) has completed the maintenance by the time it is assigned to Ladle 1 (charge 10). However, Ladle 2 hasn't physically vacated the tiling stand location. As a result, a conflict arises between them. Ladle 1, which is assigned to a subsequent charge (charge 14), needs to undergo mandatory maintenance before tapping. Inspecting the Gantt chart reveals that none of the tilting stations are realistically available before Ladle 1 starts moving for a subsequent charge.

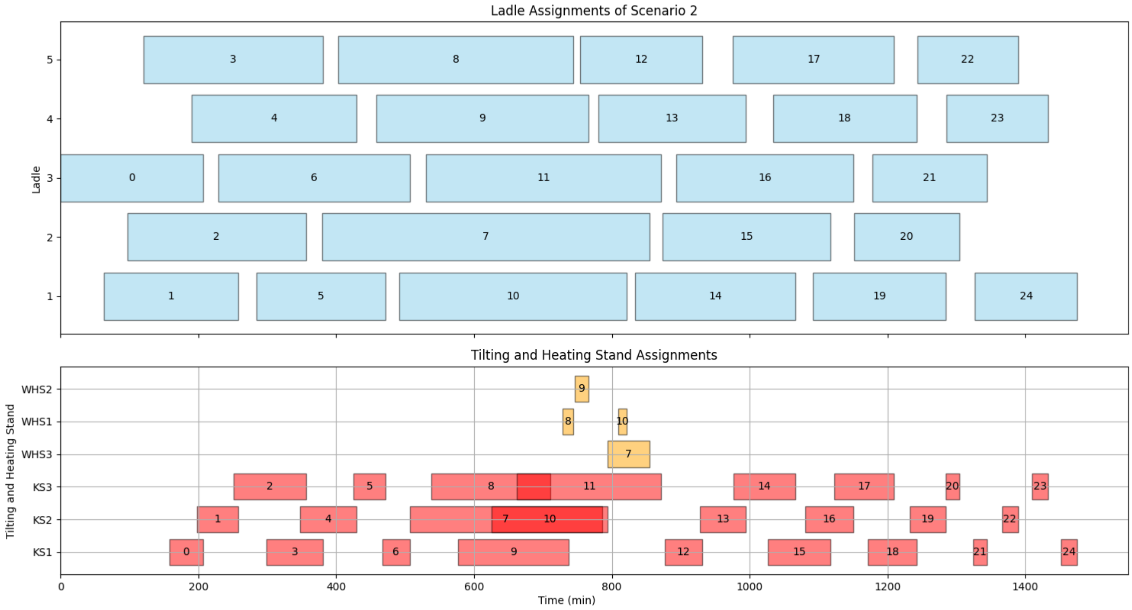

Figure 7.2: An Simulated Production Scenario with assignment conflicts

The conflicts were also further analysed to check if they are influenced by the stochastic nature of uncertain parameters such as *'maintenance durations, transport durations'*. It was observed that, even if the *'maintenance durations & transport durations'* are varied during distinct simulation runs, tilting stand conflicts remained prevalent, but the duration of conflicts were varied.

In the real-world situation of steel plants, the operators typically dispatch another ladle to ensure operational continuity. However, within the scope of the research study, the simulator must strictly follow the ladle assignments recommended by the optimization model. As ladles cannot proceed towards tapping a charge without undergoing maintenance, the production scenario remains infeasible with the ladle assignment decisions generated by the optimization model.

Among 24 production scenarios selected with MIP gap less than 1%, 9 scenarios were observed to possess the conflicts in the assignments of Tilting Stands (Figure 7.2). Consequently, these production scenarios remain unfeasible and were excluded from further analysis.

Table 7.1: Overview of Filtering Feasible Production Scenarios in Various Phases of Experimentation

Experimentation Phase	**Scenarios**
Extracted Scenarios from Historical Production Data	182
Scenarios succeeded by Optimization Model to find a feasible solution	146
Scenarios with optimization MIP gap < 1%	24
Scenarios without Tilting Stand Conflicts	15

As listed in Table 7.1, 15 out of 182 production scenarios comply with the filters and are deemed reliable for further constraint feasibility analysis and comparative system performance analysis.

7.3.2. MINIMUM TAPPING TEMPERATURE FEASIBILITY

The optimization model proposed by Ruela et al. [72] was executed to find optimal ladle dispatching schedules by respecting the minimum tapping temperature constraint of 700°C, as detailed in Section 6.2. Consequently, if the optimization model achieves a feasible solution within a runtime of 10000 seconds, the average tapping temperature of all the charges within that production scenario would be ≥ 700°C. Notably, these scenarios can be feasible owing to underlying assumptions of the optimization model.

To evaluate the feasibility of average tapping temperature being ≥ 700°C for a given production scenario, the ladle dispatching decisions are simulated by the DES model. Similar to the optimization model, if all the charges have a tapping temperature ≥ 700°C while simulated by DES model, the scenario's average tapping temperature would respect the minimum tapping temperature constraint. Consequently, the Mean Tapping Temperature of each scenario is selected as the subject for comparison and evaluation. As described in the experimental approach (Section 6.2), the DES model reports a distribution of 30 average tapping temperatures for a given production scenario.

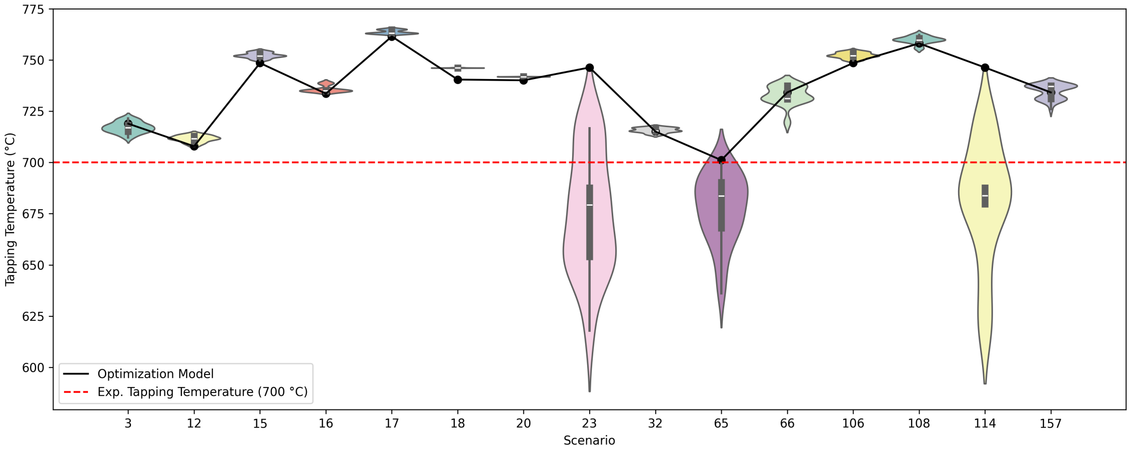

Figure 7.3: Comparison of Average Tapping Temperatures of Converged Feasible Scenarios

The average tapping temperatures reported by the optimization and simulation model are plotted against the constraint of minimum required tapping temperature, as illustrated in Figure 7.3. Among 15 production scenarios identified with an MIP gap less than 1% and free from tilting stand conflicts, three scenarios are observed to tap below the minimum required tapping temperature. For these scenarios, the majority of simulation runs are tapping below 700°C violating the minimum tapping temperature constraint.

As the scenarios which are violating the minimum tapping temperature constraint are found, it is also essential to understand the underlying phenomenon resulting in tapping at lower temperature. In order to explain this, Scenario 23 which was found to violate the constraint (Figure 7.3) was selected for demonstration purpose.

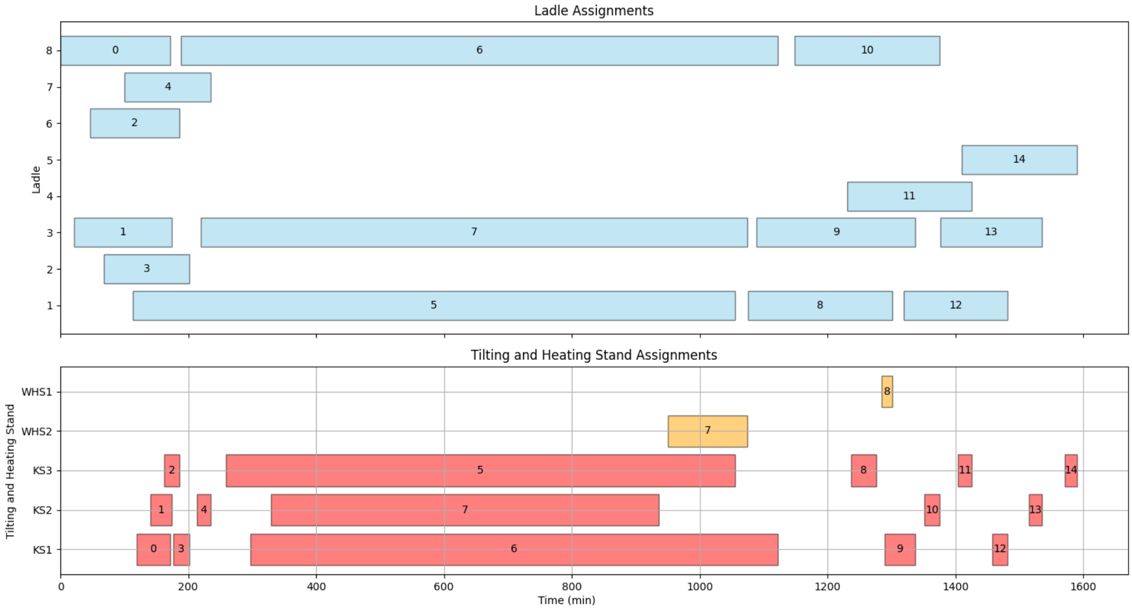

Figure 7.4: Resource Assignments for the Simulated Production Scenario 23

Figure 7.4 illustrates the resource assignments for Production Scenario 23. Notably, the scenario involves 15 charges, which is relatively lower than scenarios achieving minimum tapping temperature constraint. Similar observations are made with scenarios 65 and 114 holding 11 and 15 charges, respectively. Upon careful examination, it was found that during the operational day corresponding to these production scenarios, there was a long break in casting operations at a steel plant. Consequently, *Ladle's 1, 3, and 8*, which were engaged in charges near the casting break, were idle until they started a subsequent charge after the casting break.

The thermal tracking analysis of production scenario 23 depicted in Figure 7.5 reveals that *Ladle 1, 3, and 8* are at a significantly low temperature before tapping the charges after casting break. Notably, *Ladle 3* was able to reheat after the casting break, whereas it was not feasible to reheat *Ladle 1 & 8* even-though the reheating stands are available. It can be due to numerous factors such as: *initial temperature and available time to reheat the ladle, transport duration between different locations*. It compromises the feasibility to reheat the ladle to to 700°C before tapping. Therefore, inability to reheat and long casting brakes is the underlying phenomenon resulting in tapping at lower temperature.

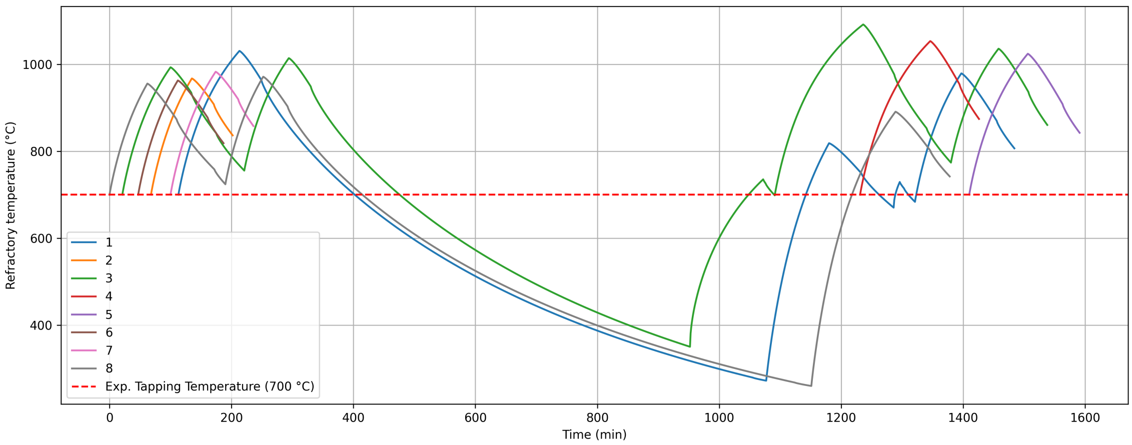

Figure 7.5: Thermal tracking of ladles in Production Scenario 23

Consequently, among the 15 production scenarios with MIP gap < 1% and no tilting stand conflicts (Table 7.1), it is observed that 80% of the scenarios are feasible in respecting minimum tapping temperature constraint. The comparison of the average tapping temperature of feasible scenarios are depicted in Figure 7.6.

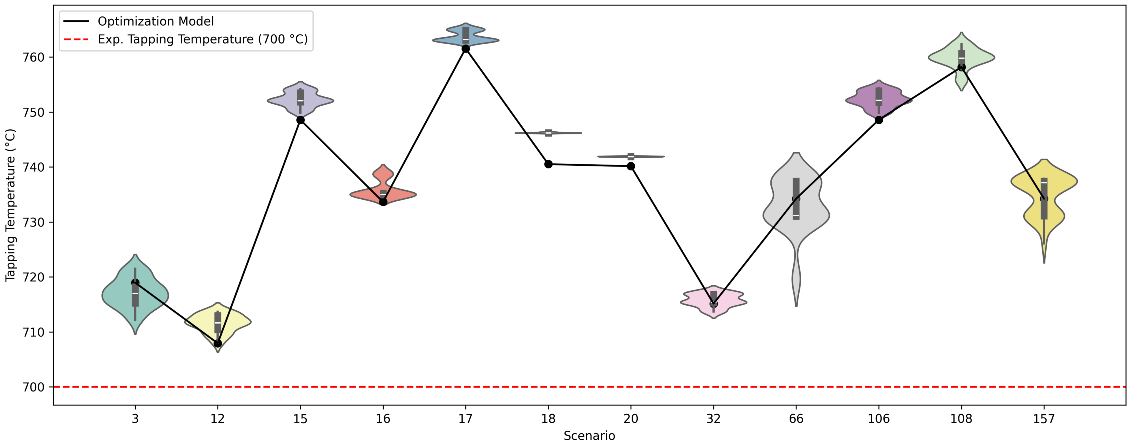

Figure 7.6: Comparison of the Average Tapping Temperature of Feasible Scenarios

It is noteworthy that, the optimization model's constraint is to carryout tapping when the refractory temperature of ladle is above 700°C for every single charge of a production scenario. Therefore, it is imperative to analyse the feasibility of tapping all the charges above 700°C when simulated through DES model, rather than the average tapping temperatures. Due to the stochastic process parameters within the DES model, the possibility to tap above 700°C remains uncertain with distinct simulation runs. Therefore, as observed in Figure 7.7 the simulation results of all 30 runs are analysed to check the tapping temperature of all the charges in the scenarios.

It was found that, for most of the production scenarios which possess average tapping temperature above 700°C for all simulation runs, there existed at least one production charge with ladle refractory temperature less than 700°C while tapping in every simulation run. Only one production scenario was found to tap above 700°C for all simulation runs, because the available time between the adjacent charges of each ladle was relatively less so that ladle was dispatched at higher temperature without reheating. Therefore it could be emphasized that, the optimization model can consider the constraint to assign ladles to charges such that average tapping temperature of the scenario remains above minimum tapping temperature., It is because, given the stochastic behavior of the system, it would be complex and unreliable to respect the constraint for every charge in a scenario.

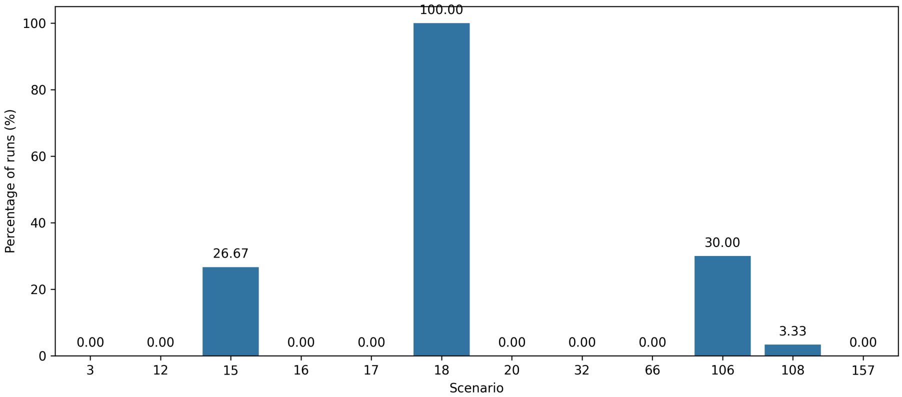

Figure 7.7: Percentage of the Simulation Runs of each scenario tapping all charges above 700°C

Additionally, in order to evaluate the objectives outlined by Ruela et al. [72], it is also imperative to juxtapose the sum of reheating durations reported by optimization and simulation models for the scenarios achieving minimum tapping temperature constraint (as illustrated in Figure 7.6). It aids in deriving insights about the duration elapsed to reheat the ladles to reached their respective refractory temperature during tapping.

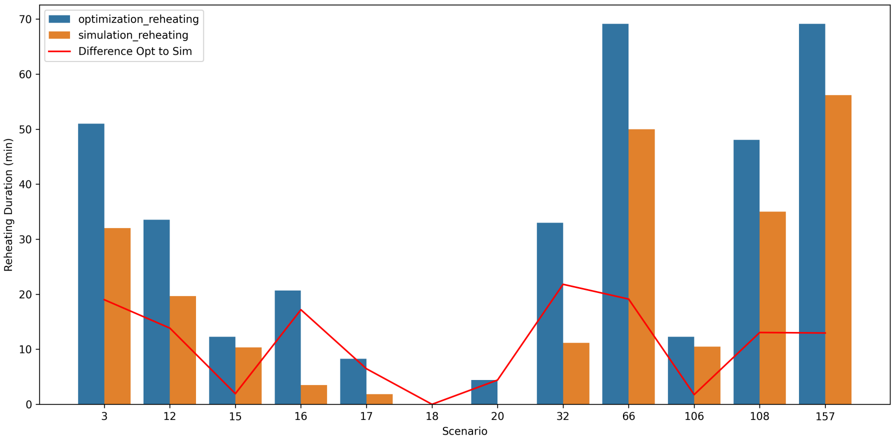

Figure 7.8: Sum of Reheating Durations of Converged Production Scenarios
(It represents: Sum of Reheating Durations, in the context of Optimization Model &
Mean of Sum of Reheating Durations, in the context of Simulation Model as it was executed 30 times)

From Figure 7.8, it is evident that, across all production scenarios, the sum of reheating durations reported by the optimization model was higher than those reported by the simulation model. The dispatching rule of both models was to reheat the ladle closest to tapping the subsequent charge. As a result, the reheating operation is contingent upon the transport duration of the ladle from the reheating stand to the converter location. As mentioned by Ruela et al. [72], the optimization model has fixed transportation durations that are shorter than realistic durations.

As a result, when the ladle dispatching decisions are evaluated by the DES model with stochastic transport durations, the reheating durations are found to be lower than that of optimization model. It is because, due to the higher and uncertain process parameters, the feasibility to reheat the ladles are being compromised. It can also be emphasized from Figure 7.7 that, there existed at least one production charge with tapping temperature less than 700°C most of the scenarios. This insight clarifies that, reheating was not feasible for at least one production charge in each scenario.

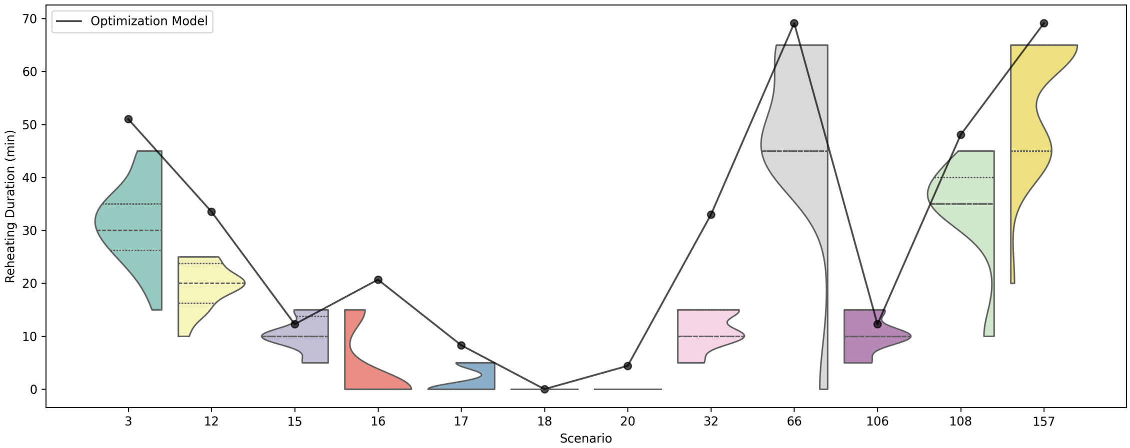

Figure 7.9: Comparison of Sum of Reheating Durations of Converged Production Scenarios
(Distributions against each scenario represents Sum of Reheating Durations of all simulation runs of respective scenario)

Additionally, as illustrated in Figure 7.9, the sum of reheating durations of optimization model and simulation model for all thirty runs (in contrast to the mean value in Figure 7.8) were compared to analyse the stochastic behavior of reheating durations owing to uncertain *'maintenance and transport durations'*. It was observed that, for most of the scenarios, the reheating durations reported by optimization model were higher, compared to the distribution of values reported by simulation model. As a result, it is evident that, it may not be possible to reheat the ladles to the durations reported by optimization model, even with varying reheating durations influenced by stochastic nature of uncertain parameters.

As the objective of the optimization model developed by Ruela et al. [72], was to optimize both reheating and idle durations with optimization weights being $\lambda_1 = 2$ and $\lambda_2 = 1$ respectively. The underlying motivation was that the ladle needs to be reheated and dispatched to subsequent charge rather than staying idle. So, it is also important to analyse the idle durations along side reheating durations to compare the optimization objectives.

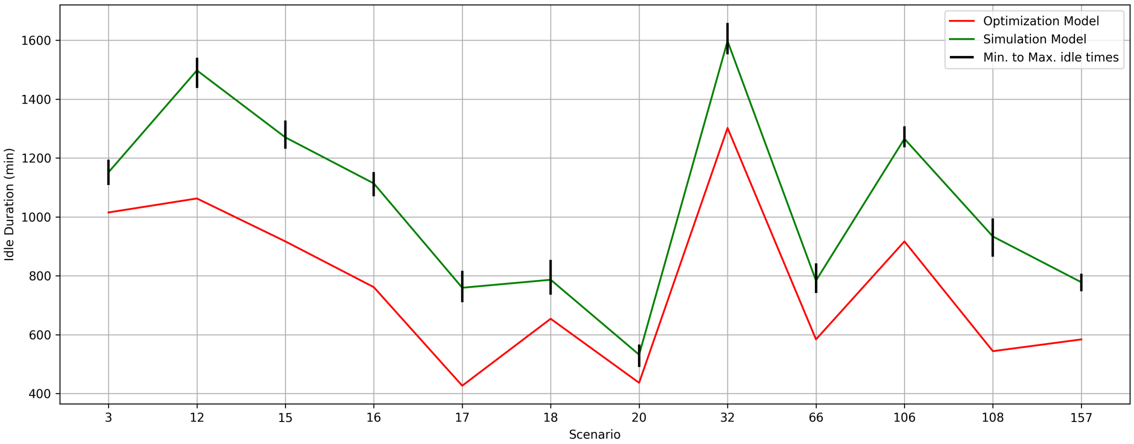

Figure 7.10: Comparison of Sum of Idle Durations of Converged Production Scenarios
(It represents: Sum of Idle Durations, in the context of Optimization Model &
Mean and Range of Sum of Idle Durations, in the context of Simulation Model as it was executed 30 times.)

Reheating durations and Idle durations, as observed in Figure 7.8 and Figure 7.10 respectively, tells that, optimization model was respecting the objectives to minimize sum of idle and reheating durations. It was observed that, in the context of optimization model, the idle durations are lesser than the reheating durations. It means that, the optimization model manages to minimize the idle duration of ladles by reheating it and dispatching to subsequent charge soon after the current charge. In contrast, upon evaluating the decisions by DES model, the idle durations observed to be higher than the reheating durations.

In the context of DES model, a ladle is assumed to stay idle when ever reheating stands not available for reheating and time is insufficient to reheat to minimum required tapping temperature. So, it can be emphasized that, the idle durations are dependent on the reheating durations, which are in turn dependent on the uncertain maintenance and transport durations. This analysis also makes it clear that, it was not possible to reheat the ladles to minimum tapping temperature for all the charges in a production scenario. As a result, it would be beneficial to consider more realistic *'maintenance and transport durations'* while generating ladle dispatching decisions, in order to make the optimization model more efficient and accurate.

7.4. COMPARATIVE ANALYSIS RESULTS

Within the scope of the present research study, it is deemed essential to analyze the impact of the optimization model generated schedules on the Sustainability Indicators of a steel plant. This necessity arises from the optimization model proposed by Ruela et al. [72], which aims to improve the energy efficiency of ladle logistics. During the execution of the optimization model, it also computes the sustainability indicators of the scenarios in terms of CO_2 Emissions and Steel Temperature Losses based on the model assumptions. Therefore, as the DES model simulates ladle dispatching decisions with more realistic parameters, it reports more accurate values of sustainability indicators.

As described in Section 6.4.2, the reheating operation at the steel plant, involves the combustion of natural gas through reheater burners, resulting in CO_2 Emissions. Subsequently, the sum of CO_2 Emissions per production scenario as computed by both optimization and simulation models are extracted. Figure 7.11 illustrates the distribution of difference in the CO_2 Emissions between the optimization and simulation model.

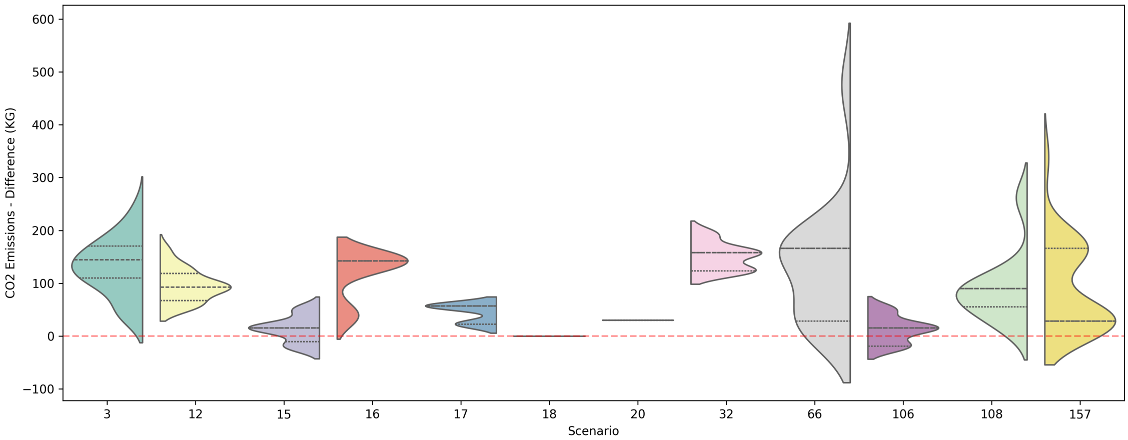

Figure 7.11: Difference in CO_2 Emissions of Converged Production Scenarios
(It represents the difference between values of optimization model and simulation model, such that for each scenario, one value of optimization model is compared against each value of 30 runs of simulation model.)

According to the analysis of reheating durations presented in Figure 7.8, the optimization model seems to estimate reheating duration by adopting unrealistic process durations and initiating reheating at lower ladle temperature, thereby resulting in higher reheating. Consequently, Figure 7.11 makes it evident that solutions generated with fixed parameters of optimization model would emit higher CO_2 than expected as per the real-world dynamics simulated by DES model. Therefore, it can be derived that, upon adopting realistic transport durations, ladles can be reheated at higher thermal state, resulting in lower reheating duration and consequently lower CO_2 emissions.

Similarly, for analyzing the temperature losses of molten steel to the steel ladle refractory walls, the cumulative steel temperature losses per scenario reported by both optimization and simulation models are extracted. The distribution of difference in temperature losses between the optimization and simulation model are illustrated in Figure 7.12. Notably, the optimization model reports higher steel temperature losses than expected, as per the simulated values of DES model. This phenomenon occurs when the ladle is at a lower temperature while tapping the charge at the converter. For the *production scenarios 3, 66, 157*, the temperature losses are less than the expected values simulated by DES model. It is because, as observed in Figure 7.6, these scenarios have an average tapping temperature higher than the median of distribution reported by simulation model, which is not the case for remaining scenarios. As a result, it is evident that, despite higher reheating durations, ladles are at lower temperatures compared to the DES model, while tapping the charge at the converter, resulting in higher heat losses to refractory linings.

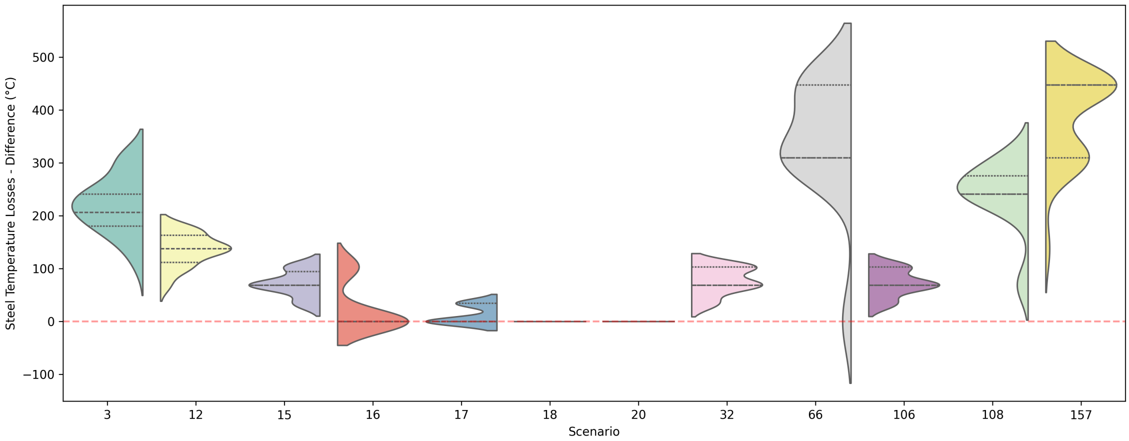

Figure 7.12: Difference in Sum of Steel Temperature Losses of Converged Production Scenarios
(It represents the difference between values of optimization model and simulation model, such that for each scenario, one value of optimization model is compared against each value of 30 runs of simulation model.)

7.5. EXPERIMENTAL INSIGHTS & EVALUATION RESULTS

The primary objective of this research study is to develop a Discrete Event Simulation (DES) model for evaluating the decisions and feasibility of objectives of an optimization model pertaining to Steel Ladle Logistics. This objective is realized through comprehensive experimentation and subsequent analysis of results. Consequently, the following observations regarding the optimization model proposed by Ruela et al. [72] are derived:

- Ladle assignments generated by the optimization model for scenarios possessing longer casting breaks, can violate the minimum tapping temperature constraint when implemented in real-time.

- The production scenarios are experiencing conflicts with the assignments of tilting stands, when ladle assignments are simulated through realistic process durations through DES model.

- The optimization model, with fixed process and transport durations, suggests longer reheating durations than expected in more realistic logistics simulated by DES model.

- Consequently, due to reported longer reheating durations by the optimization model, the CO_2 emissions by combustion of natural gas exceed those expected through more realistic logistics simulated by DES model.

- Despite the higher reheating durations, the ladle's tapping temperature is lower than expected through more realistic logistics simulated by DES model, resulting in relatively higher steel temperature losses. It is mainly due to the unrealistic lower transportation durations.

- It would be too complex and unrealistic to respect the minimum tapping temperature for each charge of a production scenario in real time. It would be beneficial for optimization model to consider maintaining average tapping temperature above the constraint, which makes them feasible to be applied to real-time.

Therefore, it can be highlighted that, in order to make the production schedules more energy efficient, such that it improves system performance, realistic process parameters can be incorporated into the optimization model.

During the experimentation phase, it was found that the simulation model has a limitation in dynamically moving the ladle from one location to another during its idle phase. The ladle should be moved by the simulator around different tilting and reheating stands by keeping it idle in the new location to vacate the location of interest for another ladle. This ability for simulation model improves the robustness of evaluation and would be required while integrated with optimization model for reactive scheduling when it is practically implemented in the steel plant. Consequently, the integrated module would be beneficial for steel plant in continuing production when an unforeseen delay occurs as it reiterates the schedule in a reactive approach. This limitation can be addressed by improving the resource management module of simulation model such that it dynamically moves ladles around tilting and reheating stands without conflicts.

In addition, simulation model in the research study assumed to keep the ladle idle, if it could not reheat it to minimum required tapping temperature. There could be situations where the ladle could be reheated to an temperature less than but near to minimum tapping temperature. But the simulation model skips it because, the motivation was to check the feasibility of reaching the minimum tapping temperature by following ladle dispatching decisions generated by optimization model. The evaluation process of the optimization models could be better if the above limitation was also considered

However, addressing these limitation remained beyond the scope of this research study. Nevertheless, these limitations would be a potential research topic for future endeavors. Despite the limitations, the DES model can be adopted by TSNL to evaluate the optimization model and its applicability in the real-time. Additionally, even after real-time implementation of optimization model, it would help TSNL to evaluate the sustainability indicators of schedules generated by optimization model and take necessary changes if they are more than anticipated.

8

CONCLUSION

The present thesis embarked on a purpose to develop a methodology to evaluate decision support systems in the realm if steel ladle logistics using simulation techniques. In the context of steel ladle logistics, optimization models are being developed for generating energy-efficient ladle logistic schedules. The primary objective is to evaluate this optimization model by analyzing the schedule feasibility and effect of sustainability indicators through a more realistic DES model replicating real-world dynamics of OSF2 plant.

The research study commenced through a comprehensive analysis of the current state of research concerning optimization in steel ladle logistics, validation techniques to evaluate decisions of optimization models, simulation techniques adopted for validation, and sustainability indicators relevant to steel plant operations. Employing a systematic literature review (SLR) approach, an extensive analysis of research articles was conducted, revealing significant research gaps and the potential applicability of simulation techniques for validation purposes. This process has laid the foundation for subsequent research endeavors in the field.

The Simulation Model development methodology proposed by Sargent [73] has been a significant contribution to the scientific landscape as it provided a robust structure for the systematic development of DES model. Adhering to this methodology, a comprehensive system analysis was conducted to establish a conceptual model of steel ladle logistics by identifying the logistical phases, dispatching rules, and process parameters thereby aiding the development phase of DES model to replicate the real-world dynamics

Despite making few pre-assumptions regarding the logistics that do not directly impact the validation objective, the system was too complex to model in a simulated environment, given the dynamics of steel-making and its logistical intricacies. One such phase was to model and integrate the resource monitoring module into DES for realistic assignments. Furthermore, despite the capabilities and potential utility of the SimPy package, its adoption was found challenging due to the lack of comprehensive tutorial resources or accessible blogs, intensifying the difficulty of the model development phase.

Therefore, following numerous iterations, the conclusive DES model has successfully integrated the dynamics of steel ladle logistics within the scope of the study. The model's functionality underwent regular validation throughout the development phase by structured walk-throughs to concerned stakeholders knowledgeable of the system being modeled. Consequently, the developed DES model was capable of evaluating the feasibility and sustainability of ladle dispatching schedules generated by the optimization model under examination. The experimentation insights elucidated a comprehensive understanding of the capabilities and limitations of the optimization model, facilitating thoughts for further enhancement.

8.1. ANSWERS TO RESEARCH QUESTIONS

8.1.1. SUB-RQ5: DEVELOPMENT APPROACH OF DES MODEL

The ultimate goal of the study is to develop an efficient simulation model that incorporates the dynamics of steel-making and steel ladle logistics within the scope of the study, and the chosen optimization model for evaluation. Through a comprehensive system analysis key process parameters and required modules to replicate the real-world dynamics of steel-ladle logistics are identified. The underlying dispatching or process initiation rules required by the simulator to carry out the system processes are also identified through system analysis.

The development of the DES model followed a structured approach, characterized by the complexity and inter-dependency of the processes being modeled. The approach involves drafting the model into different phases, with each phase dedicated to defining a specific module, which complements each another ensuring cohesive integration of the whole model.

The developed DES model has comprised three principal modules: *ResourcePool* module efficiently monitors the resources involved in the system (in this case: ladles, reheating stands, and tilting stands). Each resource kind is defined as a SimPy Store facilitating efficient deployment and utilization during an operation and followed by proper return post-usage. *Transportation* module, responsible for computing realistic travel durations between different locations in steel plant, ensuring the accuracy of the logistical processes during simulation. *ThermalTracking* module is designated to monitor the thermal state of ladles throughout the steel-making cycle for accurate decisions regarding the reheating process.

Throughout the model development process, the modules are iteratively validated through structured walk-throughs and traces with the assistance of concerned stakeholder to ensure the accuracy of business logic underlying the dispatching rules.

8.1.2. SUB-RQ4: DES MODEL TO EVALUATE OPTIMIZATION MODELS

In order to evaluate the optimization model chosen for examination, production scenarios were generated that act as the test cases for both models. The objective of DES model is to simulate the behavior of ladle dispatching decisions generated by the optimization model against real-world dynamics of steel-making. Consequently, the optimization model is executed earlier with generated production scenarios. The ladle assignments suggested by the optimization model for successfully converged scenarios served as a prerequisite to executing DES model alongside production scenarios data.

The evaluation methodology for the decisions generated by the optimization model unfolds in two phases: *Feasibility Analysis and Sustainability Comparison.* Before initiating the process, the results of the optimization model are filtered, such that the MIP gap of scenarios to be analysed lies below 1%, as the solutions are closer to the true optimal.

After the filtration process, *Feasibility Analysis* was carried out to compare the ladle dispatching behavior between optimization model and expected behavior simulated by DES model. Specifically, the feasibility of carrying out tapping by respecting the constrained minimum tapping temperature for all charges within a scenario was checked.

Furthermore, through *Sustainability Comparison* methodology, scenarios deemed feasible by the simulation model are analyzed for the sustainability of the schedules. Initially, the reheating durations reported by both models for reaching the required tapping temperature are compared. This is because the sustainability indicators identified as relevant for the research study are dependent on reheating durations. The consequences of reheating a ladle involve the emission of CO_2 due to the combustion of natural gas. So, the methodology ascertains whether the schedule suggested by the optimization model emits less or more CO_2 against real-world operational dynamics.

Additionally, the steel temperature losses during a steel-making charge depends on the tapping temperature of the ladle which is in turn dependent on reheating duration. As a result, temperature losses are also compared by justifying them with the reheating durations of a scenario. In the essence, this feasibility and comparative analysis evaluates the optimization objectives and constraints of the model proposed by Ruela et al. [72].

8.2. STUDY CONTRIBUTIONS

8.2.1. ACADEMIC CONTRIBUTION

The current research study delivers notable contributions to academia. Initially, the study provides a extensive SLR to comprehensively analyse the current literature related to techniques adopted to validate the optimization models, optimization models developed in the context of steel ladle logistics, and sustainability indicators of steel plants.

Consequently, it identifies that relatively less work was carried out to optimize the steel ladle logistics. Significantly, a lot of optimization models developed in diverse application areas remained as theoretical constructs without practical enactment due to the absence of robust validation methodology to carryout feasibility analysis of the models.

Few researchers have adopted simulated visualization of model generated decisions, but they are dependent on the assumptions of underlying model but not on the real world dynamics. One of the scholarly contributions addressed integrating Discrete Event Simulation along side optimization model to check the feasibility of schedules for steel making process. However, the work hasn't considered in-depth details of ladles and its thermal tracking in the simulation module, serving as a potential gap for research.

This research contributes to filling the gap by exploring the in-depth details related to steel ladle logistics. It aims to develop evaluation methodology using simulation techniques that replicates real-world dynamics and would be able to validate related optimization models. Furthermore, comprehensive analysis regarding the indicators that affect the sustainability of steel plants due to ladle logistics and the methodology to compute them enrich the existing body of literature on sustainability assessments within the steel industry.

These contributions to academia advance the discussions within the steel-making sector, helping the organizations evaluate the effect of optimization models related to steel ladle logistics on their respective sustainability indicators which benefits both environment and business.

8.2.2. PRACTICAL CONTRIBUTION

In the practical setting, the current research delivers significant contributions to the research underway to optimize the steel ladle logistics at TSNL. The developed model encompasses more realistic process parameters compared to the optimization model developed with the use-case of TSNL. Consequently, the methodology stays relevant in the future and can be adopted by the stakeholders upon further enhancing the optimization model for evaluating the feasibility and effect on sustainability indicators. Additionally, the methodology developed in the study can serve as an inspiration for validating optimization model concerning other logistical processes at TSNL.

In case if TSNL proceeds towards systematic development of optimization model for steel ladle logistics, this evaluation methodology helps in generating the effect of model on system performance. These conclusions act as managerial insights to the business stakeholders to decide on the practical implementation of model. Furthermore, if TSNL succeeds in practical implementation of ladle scheduling optimization model, the methodology along with the DES model with further development can serve as the reactive scheduling agent. In conclusion, the contribution can also serves as an inspiration to stakeholders at TSNL researching to optimize the logistical aspects of steel-making.

8.3. LIMITATIONS AND FUTURE RECOMMENDATIONS

Despite the research study has derived significant contributions to the academia with in the context of steel ladle logistics, certain limitations needs to be acknowledged.

The primary limitation of the study is, the research was carried out by considering the process parameters of steel ladle logistics at TSNL. Even-though the results are promising, they are relevant to the use-case of TSNL. It is essential to note that, different steel makers follow diverse manufacturing practices exhibiting unique complexities within their systems making it irrelevant to generalize the solution. As a result, researchers interested in adopting the solution developed in the study need to tailor it to their respective process parameters. Nevertheless, by following the methodology discussed in Section 3.2, researchers would be able to replicate the work and evaluate optimization model of their production scheduling problem.

Additionally, resource management module of the simulation models can be made better allocate the resources and dynamically move the ladles with in the specified locations of the steel plant. It aids in more efficient validation of the ladle dispatching decisions. Future research could also explore the potential of adopting reinforcement learning along side discrete event simulation for solving production scheduling problems such that optimization and validation can be accomplished by a single model [51].

Moreover, the DES model has a limitation due to the inability to address the crane movements. Even though it haven't impacted the validation capability of DES model, integrating them as realistic as possible would make the artifact more efficient. As the time constraints played a crucial role in development phase, it was not included in the scope of study. Therefore, future research can consider including an module that can dynamically monitor crane movements would enhance solutions reliability and effectiveness in practical implementation.

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Appendix A: Systematic Literature Review

Table A1: Overview of all the literature that have been reviewed to identify features, trends, literature gap and carryout research

Article	Study & its Motivation	Industry	Application Area	Evaluated KPI	Proposed Model / Solution Algorithm	Validation Technique
Wang, D., Liu, Z., Chen, L., Wei, M., Li, Y., [91]	Energy Efficient steel-making process by establishing an connection between production scheduling and equipment energy efficiency indicators, i.e., Equipment set which can complete a job in relatively low energy consumption is chosen and shutdown other set of equipment.	Steel and Iron Making	Steel-making scheduling	Reduced energy consumption by equipment shutdown strategy	Improved Migrating Birds Algorithm	Case study & Practical Implementation.
Kibzun, A., Rasskazova. V.,[48]	To develop an adequate and scalable mathematical model by considering all technological features and processes of the production planning. The motivation of the article was: to leverage the scalability and flexibility of model to be able to solve similar optimization problems, adaptable to the changes and fine tuning of system constraints and objectives.	Iron and Black Metallurgy	Production Planning	Optimised production schedule by transmuting each stage as energy efficient	Mixed Integer Linear Programming	Computational Experiments & Comparison of energy metrics of model generated schedules against actual data.

Berntsson, F., Wikström. P.,[12]	To develop an thermal model that can compute the current and future thermal state of the ladles. It was accomplished by studying the behavior of heat transfer within the ladles during the production process. It was emphasized that, by understanding the amount of thermal energy stored in the ladles, it can help in better prediction of steel temperatures during the process. It in turn improves the quality of the steel.	Steel and Iron Making	Steel Ladles	Improved Quality of steel by better understanding thermal state of ladle	Mathematical Model for Energy Transfer Calculation	Predictive Simulation Model to track thermal state of ladle.
Lee, S., Lee, G., Moon, S., Yoon, Y., [54]	Energy and Cost efficient steel-making process by optimization of distribution of electricity, steam and by-product gases through out the process. An optimization model to schedule the processes was proposed.	Steel and Iron Making	Electric Arc Furnace	Minimization of operating costs by optimal energy consumption	Mixed Integer Linear Programming	Case Studies to calculate total operational costs.
Krenczyk, D., Paprocka, I.,[49]	To fill gap between the theory and practice of implementing Industry 4.0 in production sector. A methodology to integrate discrete event simulation, prediction and optimization model was presented for a production line digital twin design of hybrid flow shop.	Manufacturing Industry	Production Planning	—	Ant Colony Optimization	—
Su, P., Zhou, Y., Wu, J., [80]	To study the impact of Processing Time Requirement (PTR) on makespan of the steel-making process and integrating it into the optimization model. To leverage the temporal flexibility of model, what-if-analysis based strategy was adopted to generate numerous pareto solutions to the scheduling problem. The main objective of the study is to make the steel making process energy efficient and sustainable by balancing operational cost, emissions and make span.	Steel and Iron Making	Production Scheduling	Reduced make-span, operational costs and emissions	Extended Resource Task Network (RTN) method by Multi-Objective Mixed integer linear programming (MO-MILP)	Case studies with several What-if scenarios.
Ruela, V., Van Beurden, P., Sinnema, S., Hofmann, R., Birkelbach, F., [72]	To study the energy-efficient ladle dispatching by integrating the thermal balance of the ladle along with heating and waiting time in the steel-making process. Constraining to the minimum ladle temperature requirement for taping, sum of waiting and heating times during empty ladle operations were minimized. The compromise between the carbon emissions by re-heating ladle and reduction in temperature losses of steel by improved thermal balance of steel ladles were presented.	Steel and Iron Making	Steel Ladle Dispatching	Reduced Temperature losses of molten steel and emissions from ladle re-heating.	Piece-wise linear model with logarithmic coding and state-of-the-art Mixed Integer Linear Programming (MILP) solvers	Computational Results from case study and comparison of KPI's against past values.
Lee, M., Moon, K., Lee, K., Hong, J., Pinedo, M., [53]	Critical review of a large number of steel-making planning and scheduling articles and proposing the basic models that includes the most important features. Constraints and objectives that are to be fulfilled by a model and practical implications of a production site were also identified.	Steel-Making	Steel-making scheduling	—	—	—

Liu, Z., Sampaio, P., Pishchulov, G., et al. [58]	An event-driven service-oriented architecture (ED-SOA) was developed for Industry 4.0 Small and medium sized enterprises (SMEs). Application built upon the proposed architecture helps in collaboration among SMEs for dynamic modelling of processes, integration of supply chains, platform governance rules for data security.	Manufacturing Industry	—	—	—	—
Hernández, J., Onofri, L., Engell, S., [40]	To analyse the energy efficiency capability of Electric Arc Furnace an comprehensive model for Industrial arc furnace is developed base-lining several rigorous sub models of heat exchange in EAF and practical information from industrial melt shop.	Steel-Making	Electric Arc Furnace		Mathematical Models of processes	—
Stavropoulos, P., Panagiotopoulou, V., Papacharalampopoulos, A., et al. [78]	To develop a framework for reducing Carbon emissions in energy intensive industries. It aids in quantifying carbon emissions, production costs upon adopting energy efficient equipment and digitalization, by defining numerous performance metrics. An steel industry case study was conducted as a demonstrable proof of concept of framework.	Manufacturing Industry	Steel and Iron Making	Minimizing Carbon emissions and production costs	—	—
Andreiana, D., Acevedo Galicia, L., Ollila, S., et al. [6]	To develop an decision support system using Reinforcement Learning algorithm for aiding in decision making of steel making sub-processes. The research objective is to assist the less experienced operators working in Composition Adjustment by Sealed Argon-bubbling with Oxygen Blowing. It helps in making accurate decisions to make the process optimal, energy efficient and sustainable.	Steel and Iron Making	Steel-making decision support	Reduced Carbon emissions, energy consumption and production cost	Q-Learning Algorithm	Policy Convergence during Training, Episode simulation from historical records.
He, D., [39]	To develop an intelligent selection algorithm to select optimal logistics distribution path in supply chain use-case. The motive of the study is to transmute the logistics schedule as energy efficient and cost efficient; and address vehicle scheduling problem. The study also addresses the problem by adopting multi-objective method which can be helpful for SMEs	Supply Chain Scheduling	Distribution Logistics	—	Genetic Algorithm and simulation decision making system	Case Study at an Warehouse
Liu, W., Pang, X., Li, H., Sun, L., [57]	To develop an optimization model such that steel-making scheduling is energy efficient. It addresses the issue by the motto of continuously casting adjacent charges on same machine by avoiding machine idle times and conflicts between charges. BP-Neural network is designed to intelligently re-scheduling the ladle path in case of casting conflicts.	Steel and Iron Making	Steel Ladles	Minimizing interval processing time and waiting time between each production process.	Ladle Scheduling: Multi Stage dynamic soft scheduling algorithm based on improved differential evolution. Ladle Re-Scheduling: BP Neural Network.	Performance metrics (Neural Network) and Comparison of schedules against base-line schedules.

Cheng, C., Lin, S., Pourhejazy, P., Ying, K., Lin, Y., [19]	To develop an optimal scheduling algorithm for production sites to transmute into an no-idle flow-shop, i.e., no idle-time between adjacent jobs of a machine. The motivation is to make the production process clean and energy efficient. In addition to this, research is carried out to develop an extended solution for Bi-objective No-Idle Permutation Flow-shop Scheduling Problem.	Manufacturing Industry	Production Scheduling	—	Hybrid Iterated Greedy Algorithm	Numerical results and statistical analysis to compare against baseline iterated greedy algorithm.
Holappa, L., [41]	To reach the 2050 European challenge, significant CO_2 emission cuts should be achieved. The study was to review all the plausible measures to reduce the emissions in the published literature. The article have summarized all possible means to reduce CO_2 emissions in steel-making process.	Steel-Making	Production Scheduling	Reduced overall CO_2 emissions in steel-making process	—	—
Han, D., Tang, Q., Zhang, Z., Cao, J., [36]	In order to fill the gap of considering ladle dispatching process in production scheduling, an MILP model is developed to formulate the ladle logistics schedules considering time dependencies and energy correlations between the processes.	Steel-Making	Steel Ladle Dispatching	—	Enhanced Migrating Birds Optimization	Comparison of Computational metrics
Agárdi, A., Nehéz, K., [3]	To aid manufacturing companies with accurate and real time schedules and decision support and ultimately transmute into cost efficient process. An genetic algorithm to solve unrelated parallel machines problem and minimize the set-up intervals because the switching process from one job to other can also incur costs.	Manufacturing Industry	Production Scheduling	—	Genetic Algorithms	Computational metric comparison against benchmark dataset
Armellini, D., Borzone, P., Ceschia, S., et al. [8]	To develop an generalized model for planning and scheduling of steel making and casting activities. Authors have considered numerous features and constraints of steel making operations from real plant and literature. The model can be adopted by any steel-making industry by nominal adjustments.	Steel-Making	Continuous casting scheduling	—	Simulated Annealing	Comparison of computational metrics and energy metrics.
Backman, J., Kyllönen, V., Helaakoski, H., [9]	To study the methods and tools that might be useful for improving the steel manufacturing processes and provide an comprehensive review of the tools being used at present in the industry and what can be the future perspective. The study aids in improving the resource efficiency and sustainability due to the high dependence of resources and increase in the demand for sustainable production processes.	Steel-Making	—	—	—	—
Tesselaar, W., Sluiter, A., Peekel, M., [87]	To provide an comprehensive research direction for future, authors have explained the need for optimizing steel ladle logistics. They have emphasized the importance of predicting and understanding refractory wear of steel ladles in order to make the logistics energy efficient ans sustainable.	Steel-Making	Steel Ladle Logistics	—	—	—

Chatterjee, S., Senguttuvan, A., Biswal, A., et al. [17]	In order to decrease the refractory wear, energy consumption and carbon emissions during ladle logistics, an simulation model is developed to optimise the process.	Steel-Making	Steel Ladle Logistics	Reduced refractory wear, energy consumption and carbon emissions	Simulation Modeling	—
Borodin, V., Bourtembourg, J., Hnaien, F., et al. [14]	An future perspective for development of decision support systems is presented by exploiting the integration of optimization models and simulation models. In order to demonstrate all three integration approaches ARENA and CPLEX software packages were adopted.	—	—	—	—	—
Zeng, Y., Xiao, X., Li, J., et al. [98]	In order to make the steel making process energy efficient, reduce CO_2 emissions, an optimization model is developed to generate optimal distribution schedules for byproduct gases, steam and electricity.	Steel-Making	Production Scheduling	Optimized distribution of by-product gases, steam and power	Multi-period Mixed-integer Linear Programming	Computational testing
Hou, A., Jin, S., Harmuth, H., Gruber, D., [42]	To optimize steel ladle linings to avoid premature wear of refractory linings, which in-turn makes refractory configuration economically efficient, high temperature processes efficient and ultimately save energy.	Steel-Making	Steel Ladles	Reduced energy losses	Thermo-mechanical Modelling & Taguchi Approach	—
Sun, L., Jin, H., Li, Y., [83]	In order to reduce power consumption and carbon emissions through optimal schedules of steel making continuous casting. To make the process material efficient, scrap produces in production process is reused in basic oxygen furnaces.	Steel-Making	Continuous Casting	Reduced power consumption and carbon emissions	Lagrangian relaxation method	Numerical Testing
Plitsos, S., Repoussis, P., Mourtos, I., et al. [68]	To make the manufacturing companies energy efficient and energy aware, Decision support system was developed to make the optimal schedule decisions for production process under different scenarios of resource constraints, accounting to minimization of direct and indirect energy consumption.	Manufacturing Industry	Production Scheduling	Reduced Energy Consumption besides re-using energy	Iterated Local Search Algorithm	Computational Tests for energy constraints and Simulation Estimations for energy consumption.
Fanti, M., Rotunno. G., Stecco, G., et al. [26]	To aid steel makers in staying competitive in terms of energy efficiency informed decisions must be made though steel making scheduling. In order to fulfill this objective an integrated system is develop by coupling MILP optimization model and discrete event simulation.	Steel-Making	Production Scheduling	—	Mixed Integer Linear Programming	Discrete Event Simulation Model
Su, L., Qi, Y., Jin, L., [79]	To propose an improved algorithm for batch planning process such that efficient scheduling plans are generated. It helps to effectively reducing carbon emissions, other pollutants, production costs and energy consumption.	Steel-Making	Production Planning	—	Improved fuzzy genetic optimization algorithm	Computerized scheduling system based on simulation.
Hao, J., Liu, M., Jiang, S., Wu, C., [37]	To study the uncertain scheduling problem of Steel-making continuous casting and develop an soft decision based 2 layered approach. The main objective is to make the SCC schedules more flexible to unexpected uncertain events.	Steel-Making	Continuous Casting	Reduced uncertainties in the schedules	Swarn Optimization Algorithm & Dispatching fast Heuristic	Computational Testing and comparison against State-of-the-Art Algorithms

Sun, L., Luan, F., [82]	To generate near optimal schedule of Steel-making continuous casting by decreasing or optimising the processing or make-span. Charge splitting policy based on relaxation of no conflicts and no break cast was also proposed.	Steel-Making	Production Scheduling	Reduced overall waiting time during production	Mixed integer-programming	Computational Testing
Sun, L., Luan, F., [81]	To design an framework to develop an robust and adaptive dynamic reactive scheduling model in a computationally efficient manner. It also incorporates Uncertainties such as sudden customer orders, inaccurate processing schedule estimates, un-predicted machine breakdown which makes the scheduling inefficient.	Steel-Making	Production Scheduling	—	Lagrangian relaxation neural network	Numerical Testing
Zampou, E., Plitsos, S., Karagiannaki, A., et al. [97]	To make the manufacturing process energy efficient due to the environmental concerns, strict legislation's and inflated energy costs an Intelligent framework is designed. Considering two case studies as the empirical evidence a framework is designed for developing energy aware decision making systems.	Manufacturing Industry	—	—	—	—
Figueira, G., Almada-Lobo, B., [28]	An Taxonomy is presented for integration of optimization and simulation models. Various optimization models are explained along with their capabilities. Then possible combination of those models along with simulation model is presented along with a taxonomy to check the suitability.	—	—	—	—	—
Pan, Q., Ruiz, R., [67]	To address the idle time of machines in between the adjacent jobs in the scenarios of workshops having various machines. As the idle machine time is reduced, energy efficiency will be leveraged	Manufacturing Industry	Production Scheduling	—	Iterated Greedy algorithm along with Mixed Integer Programming Model	Comparison against other meta-heuristics
Worapradya, K., [92]	To formulate a optimization model that represents the real-world situations and develop an hierarchical genetic algorithm for searching optimal steel-making continuous casting schedules.	Steel-Making	Production Scheduling	—	Genetic Algorithm	Computational Testing
Jiang, Z., Zhang, X., Jin, P., et al. [46]	To analyse the equilibrium of mass and energy and the characteristics of energy consumption. To investigate the theoretical mechanisms and practical effects of energy saving focused technologies by developing thermo-analysis software's.	Steel and Iron Making	—	Enhanced Energy efficiency by equilibrium between mass and energy	Thermodynamic Models	Case Study
Liu, W., Sun, L., Ding, J., et al. [56]	To generate an optimal matching of ladle to crane for energy conservation and consumption reduction in steel and iron making process. Considering the overhead travelling cranes, optimization of ladles logistics is studied. Because due to the various overhead travelling cranes, it is practically difficult to obtain optimal or near optimal solution for the ladle schedules.	Steel-Making	Steel Ladles	Reduced Machine Conflicts	Forward Heuristic Algorithm	Simulation Visualisation

Borenstein, D., [13]	In order to guide the researchers on proper validation of decision support systems authors have presented an practical approach for the same. Trade-off between validation, verification and evaluation are made to select the most suitable metric for the case study.	—	—	—	—	—