Chapter

Application of the Six Sigma DMAIC Methodology to the Gasification Process

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Abstract

Despite the advantages of gasification over combustion, some elements remain to improve. Fortunately, it is not necessary to reinvent the wheel to improve efficiency and quality because there are already methodologies that have been proven successful with other processes, like the Six Sigma DMAIC methodology. Therefore, this chapter explores the synergies between gasification and Six Sigma DMAIC to improve gas quality and hydrogen production, using RDF and wood as feedstock. Furthermore, the blends and equivalence ratio influence the produced gas is explored.

Keywords: Six Sigma, DMAIC, refuse-derived fuels, gasification, biomass

1. Introduction

Climate change is an urgent problem of our time since it threatens the equilibrium of our planet and, with it, the livelihood of billions of people and species [1]. Our reliance on fossil fuels, urbanization, population growth, and the increase in municipal solid waste (MSW) have influenced climate change, prompting us to reconsider how we produce and consume energy [2]. Global gross final energy consumption was 370EJ in 2017, with oil accounting for 38.7%, coal 20.3%, natural gas 21.1%, nuclear 2.1%, and renewables 17.8% (13% biomass, 3% hydro, 0.9% wind, 0.7% solar and 0.23% geothermal). The gross final energy consumption in continents in 2017 in renewable energy was: Africa 54.5%, Americas 16.0%, Asia 15.9%, Europe 12.7%, Oceania 11.9%, and the world 17.8% [3]. These figures demonstrate the dominance of fossil fuels over renewables. Therefore, substantial work remains to be done to shift the balance toward renewable energy and prevent climate change's effects.

Intergovernmental organizations and policymakers are the cornerstones of combating climate change, looking for cost-effective change by shifting toward non-conventional energy sources, for example, the EU emissions trading system (EU ETS) [4]. In this regard, some countries have formally stated a deadline to stop all coal burning. For example, the UK has set a deadline of 2025 to phase out coal use and, to expedite the process, has imposed a carbon tax of £18 per ton of carbon dioxide equivalent [5, 6]. It is worth noting that the UK remains in the EU ETS until December 31, 2020, aligning with the withdrawal agreement [7]. Likewise, Netherlands and Italy plan to phase out coal burning by 2030 and 2025 [6]. Other countries, such as Portugal, have already phased out coal use. Indeed, it completed the project 2 years ahead of schedule (from 2023 to 2021), and it now intends to use the coal-burning facilities to generate green hydrogen [8, 9].

All efforts to accelerate the phase-out of coal are also favorable from an economic point of view since the cost of emitting greenhouse gases continues to rise as policymakers increase their efforts to curb pollution-induced climate change. Carbon Pulse predicts that EU carbon prices will triple by 2030, reaching €90 [10]. Other forecasts place the price of CO_2 equivalent at between €32 and €65 per ton by 2030 [11]. **Figure 1** illustrates the upward trend in carbon emission futures prices over time.

In light of rising carbon prices, renewable energy sources appear viable for meeting global energy demand while reducing the reliance on fossil fuels in the energy sector [14]. As companies are phasing out coal burning, they turn to biomass combined with other feedstocks like MSW, reducing carbon footprint. The technology to pass from coal to biomass is already mature [6]. Indeed, Valmet upgrades old units based on bubbling fluidized bed (BFB) or circulating fluidized bed (CFB) technology or converting existing grate, oil, or pulverized coal boilers to BFB. The latest Valmet solution is biomass gasification, which partially replaces fossil fuel with biomass and RDF on a large scale, providing fuel flexibility and decreasing CO_2 emissions economically [15]. Gasification is a thermochemical conversion of carbonaceous materials into a combustible gas through partial oxidation and oxidizing agents, namely air, vapor, oxygen, or carbon dioxide [1, 16]. Gasification has numerous advantages over combustion, such as larger molecules being completely broken down into syngas. Gasification has an oxygen-deficient atmosphere. Thus, it prevents the formation of furans and dioxins since their formation demands enough oxygen. Another advantage is that the resulting syngas can produce energy or chemicals like ammonia [17].

Despite the advantages of gasification over combustion, some elements remain to improve, particularly analyzing biomass blends with other feedstocks (co-gasification) [18]. Co-gasification offers additional advantages. For example, RDF can

Figure 1.
Carbon emissions futures price (euros/ton) [12, 13].

blend materials with little added value. It also reduces CO_2 emissions by avoiding the extraction of new fossil fuels. Furthermore, blends with RDF improve the overall feedstock's LHV since RDF has a higher LHV. It also increases the CH_4 and C_2H_4 concentrations, decreasing CO concentration, which may be related to the interaction between the thermal cracking of the plastic and the catalytic ashes contained in RDF [19]. Finally, blends of RDF with biomass dilute some negative features of the RDF char, like high ash and chlorine contents, allowing its energetic valorization in existing gasification facilities [20].

Another improvement element is business process optimization, an integrated activity to make business processes manageable, reaching the best asset utilization and performance through measurable factors like efficiency and quality [21]. Fortunately, it is unnecessary to reinvent the wheel to improve efficiency and quality since many methodologies and tools for business process optimization have been designed and proved successful, for example, Six Sigma DMAIC [22] and the design of experiments. DMAIC is an essential part of the Six Sigma methodology that can be executed independently as a quality improvement method. Define, Measure, Analyze, Improve, and Control [23].

Six Sigma DMAIC methodology improves the bottom line of a product, service, or process by reducing waste and resources and increasing customer satisfaction. Although many believe Six Sigma aims to reach Six Sigma levels of quality, the truth is that Six Sigma and DMAIC aim to improve profitability. Therefore, efficiency and quality are excellent value by-products of its correct implementation [23]. According to Mikel Harry (the creator of Six Sigma), six areas drive its implementation [23]: (1) basic organizational capabilities, (2) industrial process variations, (3) business process variation, (4) engineering/design process, and documentation, (5) quality of specifications, and (6) supplier capabilities.

Even though the Six Sigma DMAIC methodology has proven successful in improving a process, it remains a considerable gap between gasification and Six Sigma DMAIC in the literature because little information or null is available. In this regard, the objective of this chapter is to explore the synergies between gasification and Six Sigma DMAIC by (1) Analyzing the Six Sigma DMAIC, history, and achievements, (2) proposing an integrated Six Sigma DMAIC framework for continuous incremental improvement and optimization of co-gasification, enhancing efficiencies of the overall process, and (3) analyzing the effects of blending biomass with refuse-derived fuels (RFD).

To achieve that, a set of experimental co-gasification runs was performed, changing blending percentages and equivalence ratio (ER) to maximize energetic efficiency based on Low Heating Value (LHV) and gas composition.

2. Six Sigma DMAIC methodology

Six Sigma has been used, tasted, and adapted to different industries and businesses from 1985 until now, optimizing processes and improving profitability. **Figure 2** [24–33] shows a historical background of the evolution and the use of Six Sigma in different fields, among them mechanical design, electrical design, manufacturing, value creation, environmental sustainability, education, etc.

A quantum leap in Six Sigma occurred in 2000 when Mikel Harry published the book *The Breakthrough Management Strategy*. That book provides a strategy called The Breakthrough Management Strategy that gathers the experiences of 15 years to reach Six Sigma Quality through a highly efficient method. In other words, Six Sigma is the

Figure 2.
Gasification history.

Land of Oz, and the Breakthrough Strategy is the Yellow Brick Road. This strategy is based on eight phases: Recognize, Define, Measure, Analyze, Improve, Control, Standardize, and Integrate (RDMAICSI) [23]. The five core phases are called DMAIC, which may implement as a standalone method [34].

The Define phase aims to understand the why of the project and what it is intended to reach. In this phase, the objectives and scope must be defined [35–37]. In the Measure phase, the applicable measurement systems and tools focusing on data collection and reporting are reviewed to identify the opportunity for improvement and the baseline performance. Critical variables are measured and collected in this phase [35, 38, 39].

The Analyze phase provides statistical methods and tools to isolate critical information that will expose the number of defective products. Here, practical business problems are shifted into statistical problems, and it is glimpsed the cause of the problems and possible solutions [35, 38]. Next, the Improve digs into the key variables that cause the problem. It may also encompass the tool Design for Six Sigma (DFSS) to guarantee a complete understanding of the problem or customer's requirements and expectations before design completion or selection of the optimum solution [3, 6, 7]. Finally, the Control phase sustains the Six Sigma initiative through continuous monitoring to avoid falling into the same problem [3, 6, 7].

The application of Six Sigma DMAIC has been quite extensive since it has proven successful in guiding companies to reduce mistakes in day-to-day operations, focusing on eliminating or reducing lapses in quality at the earliest possible time of occurrence by implementing quality control programs to detect and correct commercial, industrial, and design faults [23]. In addition, the correct implementation of Six Sigma DMAIC results in an economic benefit. For example, Motorola's savings was $15 billion over 11 years, General Electric's savings of 2 billion, Honeywell's Savings of $1.2 billion, Texas Instruments' savings of $600 million, Johnson & Johnson's savings of $ 500 million, among many more [40].

Companies have adopted the Six Sigma DMAIC methodology to improve their processes and margins. Before Six Sigma, improvements in quality programs or process improvements usually had no evident impact on a company's net income. Organizations that cannot track the effect of quality improvements on profitability do not identify what must be changed to increase their profit margins. Thus, implementing this methodology for gasification might bridge the gap between Six Sigma and gasification to the continuous incremental improvement and optimization of gasification, enhancing efficiencies of the overall process. **Table 1** shows examples of applying the Six Sigma DMAIC methodology in some processes and equipment, namely boilers, heat exchangers, ovens, compressors, cooling towers, etc.

Study	Results	Ref
Enhancing Effectiveness of Shell and Tube Heat Exchanger through Six Sigma DMAIC Phases	• Reduce the thermal energy in exhaust flue gas, significantly impacting the furnace's efficiency. • The sigma level was improved from 1.34 to 2.01. • The monetary savings was achieved by about Rs. 0.34 million per year.	[41]
Defect analysis and lean six sigma implementation experience in an automotive assembly line	• drastic reduction of unproductive activities expending 19 min work time, and a 37.2% defect ratio	[42]
Lean Six Sigma in the Energy Service Sector: A Case Study	• The company significantly improved the actualization rate from 2.6 to 20%, outperforming the 10% target in just 3 months	[43]
Improve the extrusion process in tire production using the Six Sigma methodology	• decrease of 0.89% on the indicator of work-off generated by the production system, resulting in annual savings of over 165 thousand Euros.	[44]
A systematic approach to industrial oven optimization for energy saving.	• Annual gas saving of 1,658,000 kWh (29%)	[45]

Study	Results	Ref
Improved Boiler Sootblowing	• Improve boiler efficiency by 1.2% by reducing average stack temperature to 50 F. • −0.86/0.58 (1.44 Sigma improvement) • $26,000/year fuel savings	[46]
Improve 110 psig Compressed Air System	• Reduce plant compressed air demand by 10% • 1.54/1.98 (0.44 Sigma improvement) • $140,000/year increase in recurring revenue	[46]
Improved Micronizer Steam Condensate Heat Recovery	• Reduce the steam required to heat the wash water through increased condensate recovery. • −3.2/0.25 (3.5 Sigma improvement) $577,000/year energy savings	[46]
Reduce Cooling Tower Water Header Pressure	• Reduce CTW header pressure from 68 psig (average) to 62 psig (average) • $133,000/year electrical energy savings	[46]

Table 1.
Application of the Six Sigma DMAIC methodology in processes and equipment.

3. Materials and method

3.1 Characterization of the feedstock

Three feedstocks were used (1) RDF pellets, (2) Pine Chips, and (3) pine pellets. **Table 2** contains the main aspects of the characterization of the feedstock.

3.2 Gasification pilot-scale infrastructure

The experiments were performed in a Pilot-scale Bubbling Fluidized Bed Reactor at the University of Aveiro. **Figure 3** is the P&ID of the process where each part of the instrumentation and equipment are indicated. This drawing will be helpful later in identifying potential improvements.

3.3 Methodology

To determine the best conditions, four parameters are considered gas lower heating value (LHV), specific dry gas production (Ygas), cold gas efficiency (CGE), and carbon conversion efficiency (CCE).

$$LHV_{Gas} = \frac{\sum y_{iG} * m_i * LHV_i}{m_G} \tag{1}$$

$$Y_{gas} = \frac{V_G}{m_F} \tag{2}$$

$$CGE[\%] = \frac{V_G * LHV_G}{m_F * LHV_F} * 100 \tag{3}$$

$$CCE[\%] = \frac{V_G * \frac{P_G}{R * T_G} * M_C * \sum_i \in c, i * y_i}{m_F * W_{CF}} * 100 \tag{4}$$

Material	RDF pellets	Pine chips	Pine pellets
Proximate analysis (wt.%, wet basis)			
Moisture	4.3	11.0	4.6
Volatile matter	75.2	77.9	78.5
Fixed carbon	7.1	10.8	16.6
Ash	13.4	0.3	0.3
Ultimate analysis (wt.%, dry basis)			
Ash	13.4	0.3	0.3
C	54.0	46.4	47.5
H	7.4	6.6	6.2
N	0.5	0.2	0.1
S	nd	nd	nd
O (by difference)	24.1	46.5	45.9
Ash composition (mg/kg dry basis)			
Ca	29,000	540	600
Al	20,000	22	96
Si	18,000	<200	<200
S	<6000	<6000	<6000
Fe	3100	29	73
Na	1400	280	280
Mg	950	190	280
Cl–	710	10	1500
K	680	410	590
Cu	380	<3	3
P	370	33	48
Ti	200	<3	4
Ba	190	<3	<3
Sr	180	3	5
Zn	180	5	7
Pb	42	<3	<3
Ni	34	6	<3
Cr	21	<3	<3
V	19	<3	<3
Sn	9	<1	<1
Co	8	<1	<1
Lower heating value (MJ/kg) (dry basis)	24.8	18.8	18.0
Bulk Density	864	577	911

Table 2.
Feedstock characterization.

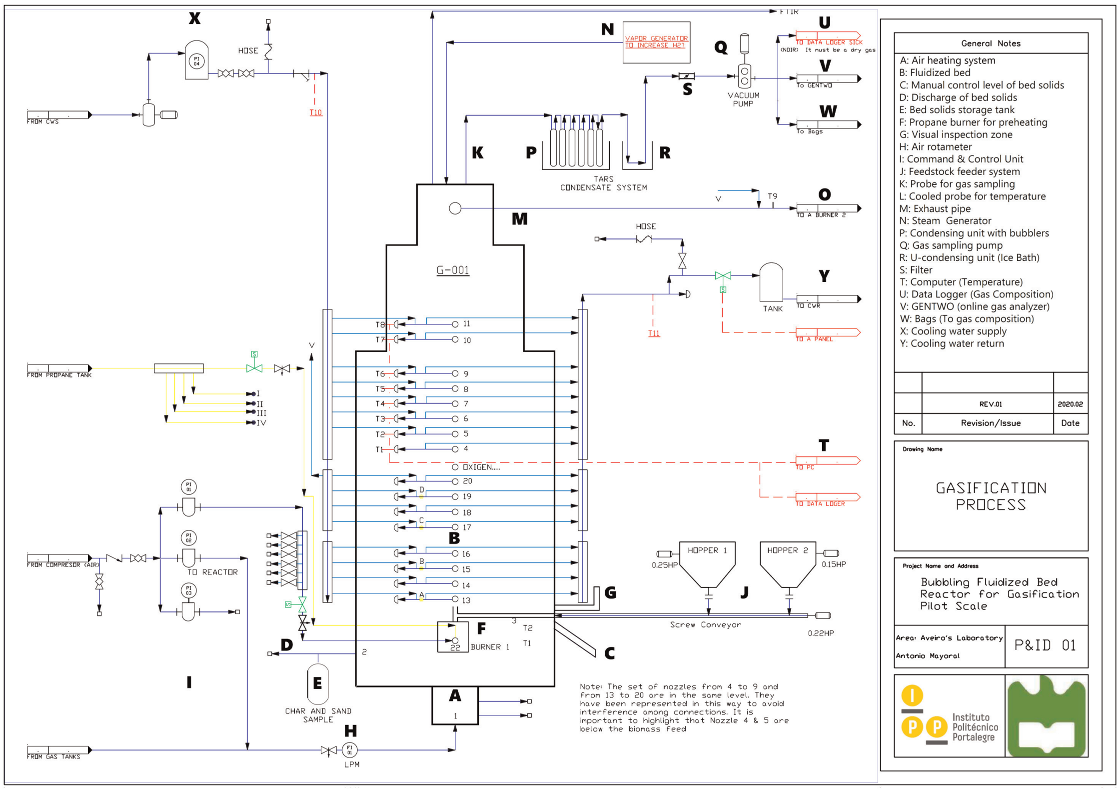

Figure 3.
Bubbling fluidized bed reactor P&ID.

4. Six Sigma DMAIC methodology applied to gasification

Six Sigma DMAIC is a systematic methodology with phases, steps, and tools. **Figure 4** shows the main steps when applying the Six Sigma DMAIC methodology. It also shows the activities and tools to use and the expected outputs; this chapter will follow some of the steps using some of these tools.

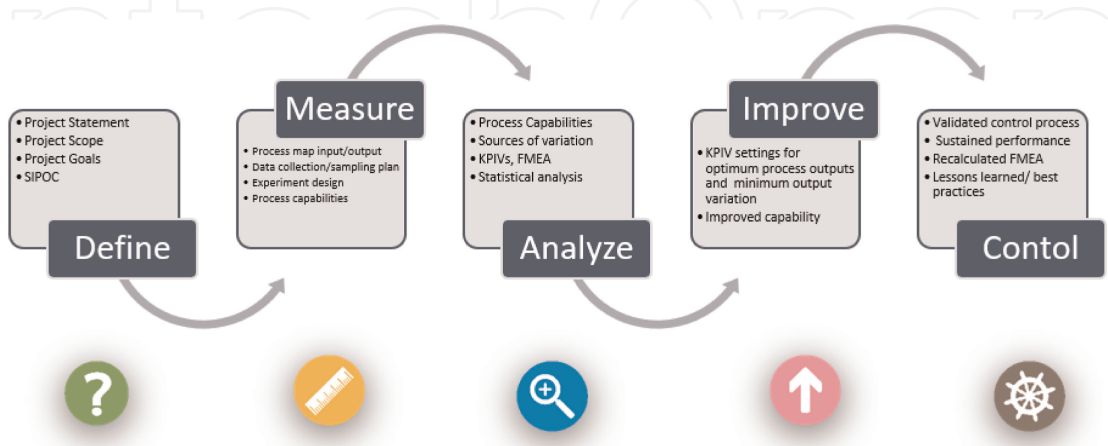

Figure 4.
DMAIC's main aspects.

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4.1 Define

4.1.1 Problem statement

Six Sigma DMAIC's success must be explored and replicated in academic gasification studies. Unfortunately, no meaningful works in this scope are available.

4.1.2 Project scope

The project scope is to use the Six Sigma DMAIC methodology to find two optimal process conditions (1) RDF/Wood Blending and (2) Equivalence Ratio by running co-gasification experiments at 785°C and atmospheric pressure, using different RDF/ Wood blending and different Equivalence Ratio, and parallelly look for improvements in the co-gasification process of the pilot-scale bubbling fluidized bed reactor of the University of Aveiro to reduce variance in the syngas composition and COPO for future studies.

4.1.3 Project goals

- The primary objective of this chapter is to explore the synergies between gasification and Six Sigma DMAIC to:
    - Propose an integrated Six Sigma DMAIC framework for continuous incremental improvement and co-gasification optimization, enhancing overall efficiency.
- Analyze the effects of blending biomass with refuse-derived fuels (RFD).

4.1.4 SIPOC (supplier, input, process, output, customer)

It is a tool that summarizes the inputs and outputs of one or more processes in table form (see **Figure 5**).

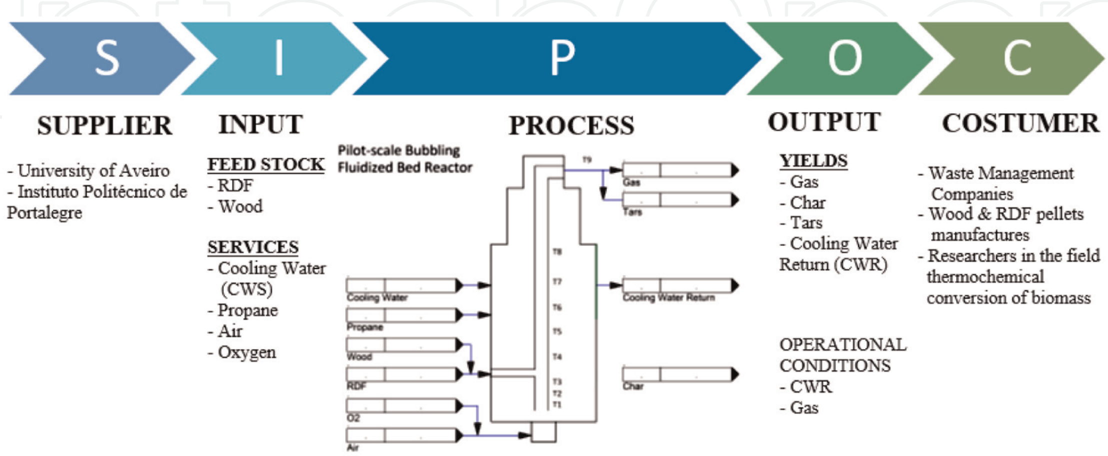

Figure 5.
SIPOC diagram.

4.1.5 Business impact

The exploration and implementation of Sigma DMAIC in Gasification can make it attractive to investors since this methodology has improved many processes, increasing profit margins. Furthermore, this can catalyze the utilization of agroforestry residues and MSW to produce energy, leading to economic and environmental benefits.

4.2 Measure

The measure phase delivers a detailed process map, presented in **Figure 3** as a piping and instrumentation diagram (P&ID), presenting input/output variables, sampling points, and other process details.

Detailed process map: The P&ID shows the parts of the process, highlighting the following process Input/output variables:

Input Variables

- Air/O_2 flow rate: This flow is measured by a flowmeter (**Figure 3H**).
- Biomass flow rate: The flowrate of biomass is calculated by the dimensions of the screw feeder and the rpm (**Figure 3J**).
- Cooling water supply temperature: Temperature is measured by a thermocouple T10 (**Figure 3**).

Output Variables

- Reactor temperature: The temperature of the reactor is measured in 8 parts; they can also be visualized in the SIPOC diagram, where T1 & T2 are the temperatures of Air/O_2 before going inside the reactor, T3 is the temperature before biomass goes inside the reactor and, T4, T5, T6, T7, T8 are the temperatures along the reactor.
- Exhaust pipe temperature: It is tagged as T9 and is the temperature of the syngas.
- Cooling water temperature: The cooling water supply temperature is T10, and the temperature of the cooling water return is T11.
- Syngas composition: Syngas from gasification contains CO, CO_2, CH_4, H_2, and N_2, mostly.

Data collection/sampling plan: The syngas is collected and analyzed in the areas named U, V, and W.

Design of experiments: The first part of the project is to identify the optimal conditions of two process variables (1) a Mixture of RDF and wood and (2) Equivalence ratios. Syngas' quality typically determines the optimal conditions considering five indicators: carbon conversion, H_2/CO ratio, CH_4/H_2 ratio, gas yield, and gasification efficiency [47]. **Table 3** shows the DoE to determine the best RDF/Wood mixture and ER.

TAG	G-CG reference	Biomass Type	%wt RDF	ER
1	PC100: ER023	Pine Chips	0	0.21
2	PC100: ER031	Pine Chips	0	0.31
3	PC90 - RDF10: ER022	Pine Chips	10	0.22
4	PC90 - RDF10: ER025	Pine Chips	10	0.25
5	PC90 - RDF10: ER030	Pine Chips	10	0.30
6	PC80 - RDF20: ER022	Pine Chips	20	0.22
7	PC80 - RDF20: ER025	Pine Chips	20	0.25
8	PC80 - RDF20: ER031	Pine Chips	20	0.31
9	PC50 - RDF50: ER032	Pine Chips	50	0.32
10	PP100: ER022	Wood pellets	0	0.22
11	PP100: ER030	Wood pellets	0	0.30
12	PP90 - RDF10: ER022	Wood pellets	10	0.22
13	PP90 - RDF10: ER031	Wood pellets	10	0.31
14	PP80 - RDF20: ER022	Wood pellets	20	0.22
15	PP80 - RDF20: ER031	Wood pellets	20	0.31
16	PP50 - RDF50: ER021	Wood pellets	50	0.21
17	PP50 - RDF50: ER030	Wood pellets	50	0.30
18	RDF100: ER023	—	100	0.23
19	RDF100: ER027	—	100	0.27

Table 3.
DoE for best mixture and equivalence ratio.

4.3 Analyze

The analysis phase delivers process setup baselines, capability analysis, and identifying sources of variation. So, the first step is to calculate the process's baseline Sigma to understand how well it performs and how much work will be required to reach Six Sigma quality.

4.3.1 Experimental results

This section presents the gasifier's operating conditions, temperature profiles over time, gas composition (CO, CO_2, CH_4, and C_2H4) profile, and the average gas composition. Finally, the dry gas LHV and efficiency parameters (Ygas, CGE, and CCE) are exhibited. The results are presented in **Table 4** and are discussed below.

4.3.2 Operational conditions

The pilot-scale gasifier of the University of Aveiro operates under the auto-thermal regime. Therefore, an external heating supply was not necessary. The average temperature was 785°C, sustained by the feedstock's ash fusibility

TAG	Bed Tem [°C]	%wt RDF	ER	H_2	N_2	CH_4	CO	CO_2	C_2H4	C_2H_6	C_3H_8	SUM	Molar Weight (Dry) [kg/kmol]	Q [NL Dry gas/min]	LHV [MJ/Nm3]	Ygás [Nm^3 dry gas/kg feedstock db]	CGE [%]	CCE [%]	std CO	std CO_2	std CH4	std C2H4	Std H2	Std N2	Std C2H6	Std C3H8
1	803	0	0.21	6.5	53.0	5.3	18.6	15.9	2.2	0.2708	0.0470	101.8	28.7	298.9	6.2	1.52	52.9	78.4	0.7	0.5	0.2	0.1	0.3	2.0	0.0	0.0
2	806	0	0.31	5.7	59.8	3.9	13.7	16.6	1.5	0.0794	0.0152	101.3	29.1	264.5	4.7	1.77	46.3	76.7	0.9	1.4	0.3	0.2	0.5	5.3	0.0	0.0
3	803	10	0.22	5.8	57.2	4.6	15.9	15.4	2.1	0.3098	0.0449	101.4	28.8	277.0	5.6	1.35	41.0	63.1	0.9	0.2	0.4	0.2	0.4	3.6	0.0	0.0
4	804	10	0.25	5.3	58.1	4.4	15.5	15.5	2.2	0.1492	0.0551	101.3	28.9	272.4	5.4	1.56	46.0	71.3	0.5	0.1	0.2	0.2	0.2	2.2	0.0	0.0
5	807	10	0.30	4.0	63.5	3.8	13.2	16.4	1.8	0.0875	0.0167	102.8	29.9	249.2	4.5	1.67	41.0	70.7	0.4	0.1	0.2	0.1	0.2	2.8	0.0	0.0
6	785	20	0.22	5.9	54.4	4.7	16.4	15.7	2.7	0.3981	0.0394	100.3	28.5	291.1	6.0	1.47	46.6	70.8	0.4	0.1	0.2	0.2	0.2	2.1	0.0	0.0
7	794	20	0.25	5.7	56.9	4.3	15.1	15.6	2.5	0.2270	0.0602	100.4	28.6	278.3	5.6	1.62	47.8	74.0	0.6	0.1	0.3	0.3	0.3	3.2	0.0	0.0
8	811	20	0.31	4.9	61.6	3.8	12.6	15.8	2.1	0.0934	0.0325	100.9	29.0	256.9	4.7	1.85	45.9	75.6	0.4	0.1	0.2	0.2	0.2	2.8	0.0	0.0
9	819	50	0.32	4.8	62.1	4.0	13.8	15.4	2.0	0.1263	0.0467	102.3	29.4	254.9	4.9	2.10	49.9	84.1	0.4	0.1	0.1	0.1	0.1	1.9	0.0	0.0
10	791	0	0.22	7.1	56.8	4.5	15.5	15.4	1.8	0.1637	0.0231	101.3	28.4	278.4	5.4	1.36	41.2	60.4	0.2	0.1	0.1	0.0	0.1	0.7	0.0	0.0
11	829	0	0.30	5.1	65.4	3.0	11.4	15.6	1.2	0.0532	0.0000	101.6	29.3	241.8	3.7	1.56	32.6	56.8	0.3	0.3	0.3	0.2	0.4	5.7	0.0	0.0
12	797	10	0.22	6.5	59.3	4.1	14.2	15.7	2.1	0.2507	0.0416	102.2	29.0	267.0	5.2	1.30	36.7	56.0	0.6	0.3	0.2	0.1	0.3	2.3	0.0	0.0
13	816	10	0.31	6.7	60.3	3.6	13.9	16.0	1.6	0.1115	0.0184	102.2	29.0	262.3	4.7	1.85	47.0	75.8	0.8	0.6	0.1	0.1	0.3	2.6	0.0	0.0
14	801	20	0.22	6.9	58.6	4.4	13.9	15.5	2.3	0.1618	0.0256	101.8	28.7	270.3	5.5	1.37	39.5	58.6	0.3	0.1	0.1	0.1	0.1	1.1	0.0	0.0
15	806	20	0.31	5.3	63.2	3.5	11.4	15.8	2.1	0.1308	0.0250	101.4	29.1	250.4	4.5	1.79	42.6	69.1	1.7	1.8	0.7	0.6	1.0	11.5	0.0	0.0
16	812	50	0.21	5.4	56.4	4.7	11.7	16.4	3.7	0.2394	0.0542	98.6	28.3	281.2	5.9	1.52	43.9	65.9	0.6	0.6	0.2	0.1	0.2	2.1	0.0	0.0
17	818	50	0.30	5.8	61.7	4.1	11.6	15.0	2.8	0.1577	0.0303	101.2	28.8	256.4	5.2	2.01	50.9	77.8	0.4	0.1	0.1	0.1	0.2	1.7	0.0	0.0
18	818	100	0.23	5.2	64.6	5.1	6.9	15.2	4.3	0.1451	0.0951	101.5	28.9	245.6	5.8	1.70	42.3	61.3	0.3	0.6	0.3	0.4	0.3	3.7	0.0	0.0
19	793	100	0.27	4.8	64.6	5.6	7.3	14.7	5.0	0.1961	0.0357	102.2	29.1	245.4	6.4	1.95	53.5	73.7	0.5	0.5	0.5	0.4	0.3	4.3	0.0	0.0

Table 4.
Experimental results.

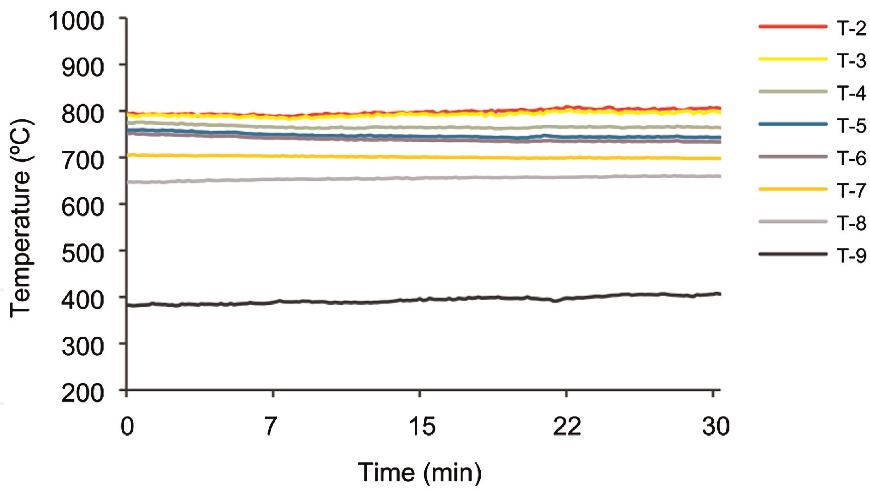

Figure 6.
Temperature profile over time.

temperatures (>1000°C). **Figure 6** depicts the temperature profiles over time (see also Bubbling Fluidized Bed Reactor P&ID).

The temperature profiles for the different experiments showed similar behavior. Yet, the experiments performed with pine chips had higher temperature fluctuations than those performed with pine pellets. Pine chip particle size is heterogeneous. At the same time, wood pellets have a more homogeneous particle size, which can justify the temperature fluctuations.

4.3.3 Gas composition

Adding RDF to the fuel mixes significantly reduced the CO content in the produced gas for comparable ER. The phenomenon may be related to the methanation reactions described below.

$$2CO + 2H_2 \rightarrow CH_4 + CO_2 \tag{5}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{6}$$

However, there is a discrepancy between experiment PC90 - RDF10: ER022 and experiment PC80 - RDF20: ER022. Both experiments were performed at ER = 0.22, having 10 and 20% of RDF, respectively. Therefore, a lower CO concentration in the mixture of 20% RDF was expected (See **Table 4**).

On the other hand, If ER increases, then CO decreases even more. However, there is a discrepancy between experiments PC80 - RDF20: ER031 and PC50 - RDF50: ER032, which were run at 20% of RDF and ER = 0.31 for the first one and 50% of RDF and ER=0.31 for the second one. The results show that the CO concentration was 12.6 and 13.6%, respectively. These discrepancies may be related to a wrong ER since a higher ER means more nitrogen. Never less. In these examples, the nitrogen concentration is lower in blends with higher RDF.

Generally, **Figure 7** illustrates the effect of the RDF weight % in the fuel mixture on the composition of the produced gas. The gasification of pine chips with 0.23 ER produced the highest CO concentration (18.6 vol%, experiment reference PC100: ER0.23), whereas RDF with 0.23 ER produced the lowest CO concentration (6.9 vol%, experiment reference RDF100: ER0.23). Increasing the amount of RDF in the

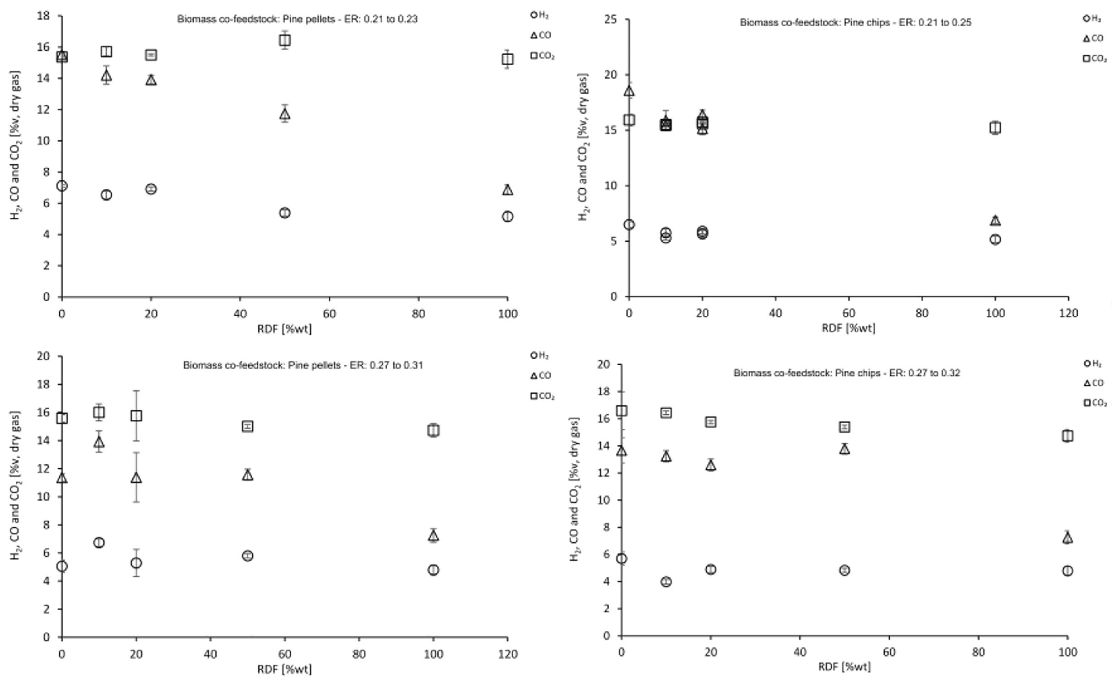

Figure 7.
Influence of the RDF weight percentage on the gas composition (H_2, CO, and CO_2).

feedstock combination from 10 to 20%, 20 to 50%, and 50 to 100% resulted in CO reductions of 6.3, 1.5, and 42.0%, respectively. In contrast, increasing the RDF weight percentage from 0 to 10% in the fuel combination resulted in an average CO increase of 5.5%.

The effect of adding RDF on CH_4 and C_2H_4 results in a higher composition as wt%. of RDF increases. For the gasification of RDF with ER 0.27 (experiment reference RDF100: ER 0.27), the maximum CH_4 and C_2H_4 concentrations were 5.6 and 5%, respectively. On the one hand, this may be rationalized by the thermal breaking of polymers in RDF pellets, which yields light hydrocarbons. On the other hand, the increased quantity of ashes rich in alkali and alkali earth metals (e.g., calcium, sodium, magnesium, potassium) found in RDF pellets compared to biomass (**Table 2**) may stimulate a catalytic effect that also results in the synthesis of light hydrocarbons. However, **Figure 8** shows a higher amount of CH_4 for blends of pine chips with no RDF, which can be an error derivate from a wrong ER measured or wrong feedstock measure derivate from the particle size and shape since this problem is seen to be reduced with pine pellets.

4.3.4 LHV, Ygas, CGE, and CCE

As shown in **Table 2**, although RDF contains a considerable amount of ash, it also contains more carbon and hydrogen than pine chips and pellets. Therefore, mixtures with more RDF will need more air in a given ER than those with less RDF in the same ER. For example, if it is assumed that carbon of 100 g of samples of RDF, pine chips, and pine pellets will burn completely (ER = 1), then 18.84% more oxygen will be required for RDF than for pine chips. At the same time, 13.68% more oxygen will be needed for RDF than for pine pellets (see **Table 5**). This situation indicates that blends with more RDF will deliver higher Ygas values than those with less RDF.

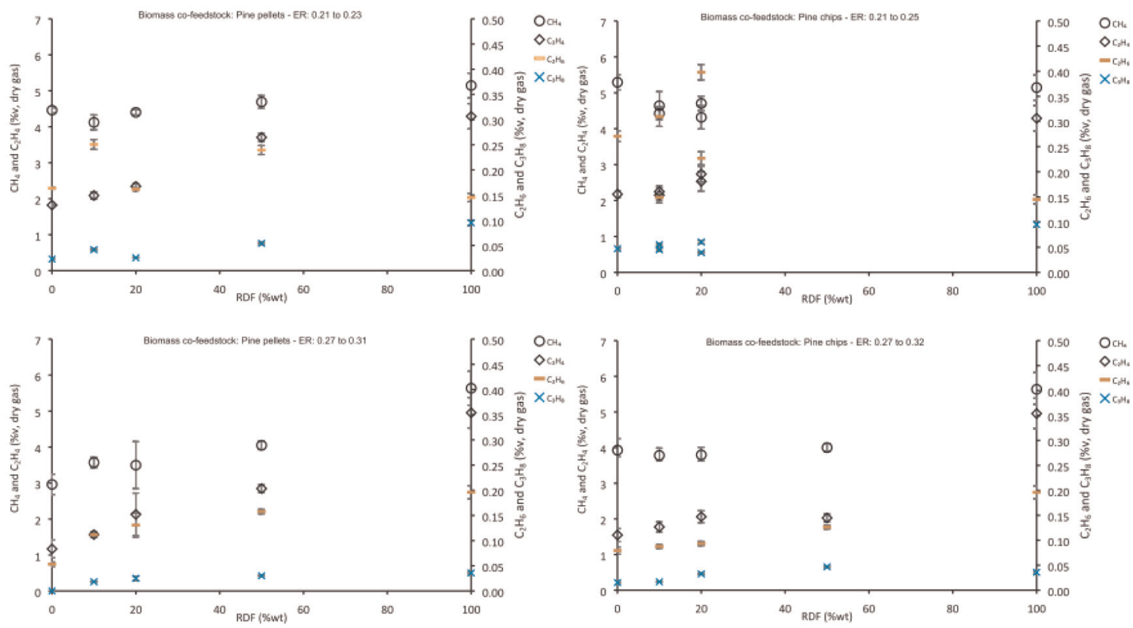

Figure 8.
Influence of the RDF weight percentage on the gas composition (CH_4, C_2H_4, C_2H_6, and C_3H_8).

Feedstock	C(g)	O2(g)
RDF	54	143.863
Pine Pellets	45.4	120.951
Pine chips	47.5	126.546

Table 5.
Required oxygen for complete combustion of 100 g of sample of each feedstock.

This analysis indicates that blends with more RDF will deliver higher Ygas values than those with less RDF. However, **Figure 9** is not entirely aligned with this analysis, which may indicate a potential error in the ER or the fed feedstock amount.

On the other hand, the LHV of the generated gas improved with increasing ER (from 5.8 to 6.4 MJ/Nm^3), mainly due to an increase in CH_4 and C_2H_4. This behavior is not expected in operations involving biomass gasification. It may be due to the higher ER promoting the thermal breaking of the organic molecules in the plastic fractions of RDF. Thus, this effect increases in blends with higher RDF amounts. However, this effect is unclear, so it may be an error in ER or the fed feedstock.

Figure 10 depicts the influence of RDF wt.% on CGE and CCE. Adding RDF to the fuel mixture has no appreciable effect on the CGE. However, there is a slight tendency for CGE to grow when the RDF weight % rises. The RDF gasification with an ER of 0.27 yielded the highest CGE value (53.5%). (Experiment reference RDF100: ER0.27). The lowest CGE value (32.6%) was reported for the gasification of pine pellets with an ER of 0.30. (Experiment reference PP100: ER0.30).

Gas Composition: Higher RDF wt.% increases CH_4 and C_2H_4 and reduces CO concentration. This effect might be due to the thermal cracking of the plastic polymers in the RDF pellets and the catalytic effect promoted by the ashes (alkali and alkali earth metals). In contrast, no significant trends were observed for the variation of H_2.

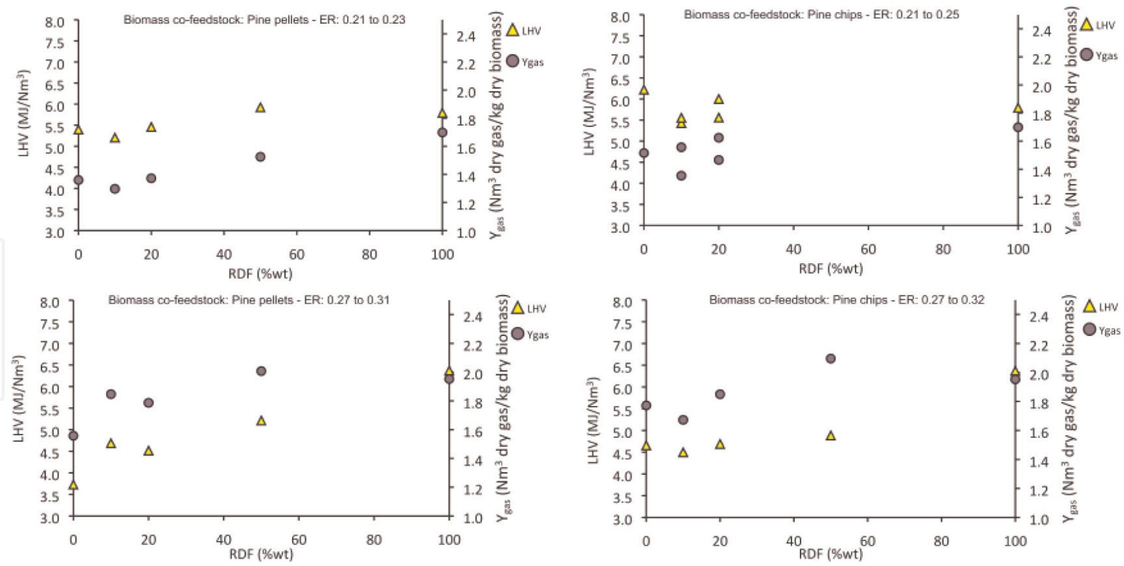

Figure 9.
Influence of the RDF weight percentage on the LHV and Ygas.

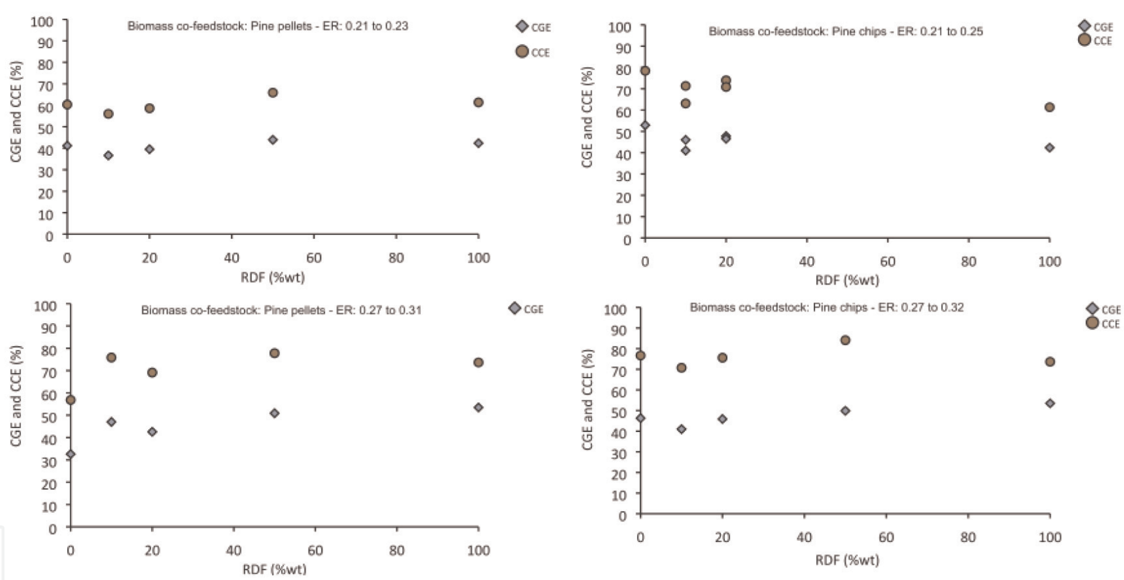

Figure 10.
Influence of the RDF weight percentage on the CGE and CCE.

- LHV: Higher RDF wt.% increases LHV because of the increasing CH_4 and C_2H_4 concentration.
- Ygas: Higher RDF weight percentage also led to slightly higher Ygas values. This result might be concealed by involuntary changes in the ER, which has a prominent effect on the Ygas.
- CGE and CCE: Higher RDF wt.% seems optimistic, although this is unclear due to conflicting effects.

In conclusion, the following tendencies are noticed, and numbers outside the trend may sometimes suggest a measurement mistake, causing variance in the process.

4.3.5 Source of variation

The variance in the Aveiro's Pilot-scale Bubbling Fluidized Bed Reactor for gasification can be visualized by monitoring the temperature and syngas composition:

1. Temperature: It is a crucial process variable that modifies the syngas composition, and its variance might result from the following improvement opportunities.

   Cooling system: Gasification is partial oxidation when an excess char is produced. It is also oxidized and produces CO_2, H_2O, and heat, increasing the reactor's temperature. The current equipment has a complicated cooling system comprising 16 small pipes along and around the reactor, supplying and returning cooling water (**Figure 2**). When the temperature increases, the operator introduces a few centimeters of some 16 pipes. This kind of technology depends entirely on the operator's expertise. Thus, the temperature variance of the reactor will change from operator to operator. Furthermore, some 16 small pipes are inaccessible to the operator, clearly a poor engineering design.

   Equivalence ratio: To produce an oxidation reaction, it is necessary to have oxygen, so the temperature will also depend on the equivalence ratio. A single flowmeter indicates oxygen and airflow, so the chosen equivalence ratio will be inaccurate. Furthermore, flowmeters are just indicators. Thus, the flow control is performed by partially opening or closing a valve. Therefore, the flowmeter measurement adds an error to the flow ratio because an operator performs this opening and closing of the valve. Hence, the precision depends on how well an operator's eyesight is.

   Refuse-derived Fuel Composition: The composition of RDF is given by moisture, volatile matter, fixed carbon, elementary composition, impurities, and ashes, and those elements might impact the temperature by promoting specific exothermic reactions.

2. Syngas Composition

   Equivalence Ratio: The equivalence ratio corresponds to the ratio between the oxygen content in the oxidant supply required for complete stoichiometric combustion. Usually, ER is between 0.2 and 0.4. ER < 0.2 results in incomplete gasification, excessive char formation, and low calorific value of the product gas. Whereas ER > 0.4 results in excessive formation of CO_2 and H_2O, rather than CO and H_2, it also decreases the calorific value of the gas.

   Refused Derived Fuel: The composition of RDF is given by moisture, volatile matter and fixed carbon, elementary composition, impurities, and ashes, and those elements might impact the gas composition by promoting the production of products with low calorific value.

   The following fishbone diagram (**Figure 11**) helps to understand the source of the variance.

   The Analyze phase offers statistical methodologies and tools for isolating vital data that will reveal the number of defective products. Business issues are transformed into statistical problems, exposing their causes and potential

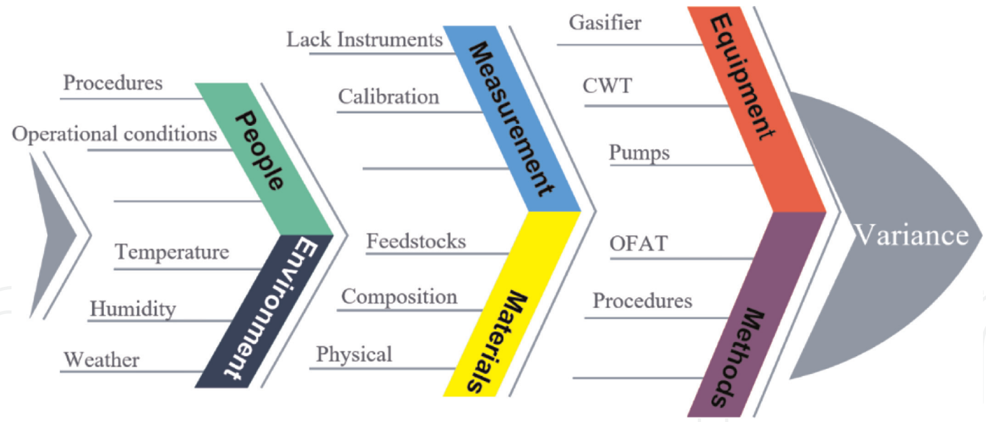

Figure 11.
Fishbone diagram.

solutions. The process settings, experimental findings, efficiency metrics, and gas composition standard deviation are detailed in **Table 3**. In contrast, **Table 6** presents an FMEA that hints at alternative solutions to the source of variance.

4.4 Improve

To look for improvements in a process, it is necessary first to understand the engineering/design process. Unfortunately, the current process lacks this documentation, making it hard to identify a flaw in the engineering design or if the operation is out of design operating conditions. However, the problems and variability caused by the lack and understanding of this documentation continuously show up, which is a wake-up call to adopt a process methodology like Six Sigma. That is why the Engineering/design process and documentation are some of the drivers of Six Sigma. (1) Key technology and process description, (2) General mass balance, (3) General energy balance, (4) Thermal Rating, (5) Process flowsheets, (6) Piping and (7) Instrument Diagrams, (8) Definition and sizing of significant equipment resulting in the process specifications, (9) Definition of control and safety devices, (10) Mechanical data sheets of the leading equipment, (11) HAZOP.

Poor industrial process capabilities often result in high COPO (rework, scrap, field failure).

Piping clogging: Gasification also produces tars, a combination of char and oils. When the gas temperature decreases, tars condensate and clog the exhaust pipe (**Figure 2**, section M). This problem can be caused by poor heating in the exhaust pipe, inappropriate feedstock flow for the facilities, or the wrong size of pipes and equipment. This results in high COPO (rework, scrap, field failure).

4.4.1 Brain-writing

Temperature control: (1) Replace the cooling temperature system with an internal serpentine can help to provide temperature homogeneity. In addition, this serpentine can be sectioned along the reactor body to provide better temperature profile control. **Figure 12** depicts the internal serpentine with a cooling water supply nozzle and a cooling water supply return.

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Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Severity (1–10)	Potential Causes	OCCURRENCE (1–10)	Current Controls	DETECTION (1–10)	RPN	Action Recommended
What is the process step or feature under investigation?	**In what ways could the step or feature go wrong?**	**What is the impact on the customer if this failure is not prevented or corrected?**		**What causes the step or feature to go wrong? (How could it occur?)**		**What controls exist that either prevent or detect the failure?**			**What are the recommended actions for reducing the occurrence of the cause?**
Biomass Size	(a)Clog the feeding system if too big	Rework, loss of time and resources	10	Inappropriate selection of particle size	1	Pre-processing with sieves	1	10	Establish a particle size range
	(b) Deficient Heat transfer	Increase residence time	7	Inappropriate selection of particle size	1	Pre-processing with sieves	1	7	Establish a particle size range
Biomass Shape	(a)Clog the feeding system	Loss of time and resources	10	No pre-processing of feedstock	1	Pre-processing by chopping	1	10	Establish a particle size shape range
	(b) Increase equipment size	Increase the cost of equipment	10	No pre-processing of feedstock	1	Pre-processing by chopping	1	10	Establish a particle size shape range
Biomass Flow Rate	(a)Clog the feeding system	Loss of time and resources	10	Inappropriate equipment design	2	Screw calculation	8	160	Select a proper Flow Indicator Transmitter
	(b) Reactions	Increase residence timeand cost	7	Inappropriate Flow rate selection	2	Screw calculation	8	112	Select a proper Flow Indicator Transmitter
Equivalence Ratio (air feed)	(a) Incomplete gasification	Excessive char formation and low calorific value of the product gas	10	Inaccurate RE calculation	5	Flowmeters	8	400	Select a proper Flow Indicator Transmitter
	(b) Excessive formation of CO_2 and H_2O, rather than CO and H2	Decreases the calorific value of the gas	10	Flow meters are not calibrated or were incorrectly chosen	5	Flowmeters	8	400	Select a proper Flow Indicator Transmitter

Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Severity (1–10)	Potential Causes	OCCURRENCE (1–10)	Current Controls	DETECTION (1–10)	RPN	Action Recommended
What is the process step or feature under investigation?	**In what ways could the step or feature go wrong?**	**What is the impact on the customer if this failure is not prevented or corrected?**		**What causes the step or feature to go wrong? (How could it occur?)**		**What controls exist that either prevent or detect the failure?**			**What are the recommended actions for reducing the occurrence of the cause?**
Gasification Agent	(a) Excessive production of tar	Lower calorific value and clogged exhaust pipe because of Tars production	7	Flow meters are not calibrated or were incorrectly chosen	5	Flowmeters	8	280	Select a proper Flow Indicator Transmitter
Temperature	(a) Too high	Operational problems	10	Char and combustible gases combustion More air than what should be	5	Thermocouples	8	400	Redesign and automate the cooling system
	(b) Too low	No gasification reactions	10	Feed combustion gas to the chamber	5	Thermocouples	8	400	Redesign and automate the cooling system
Ash Content	(a) Too High	The catalytic effect, changing gas composition	10	RDF with a higher number of ashes	1	No control	1	10	Establish an ash content range
Moisture	(a) Too High	Waste of energy and gas composition changes	10	Improper storage of biomass	1	No control	1	10	Establish an ash content range

Table 6.
FMEA.

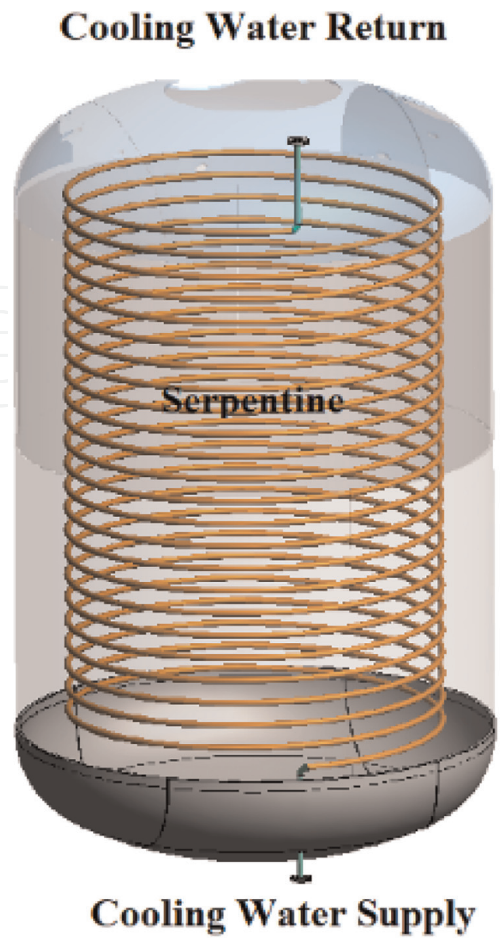

Figure 12.
Serpentine.

(2) Furthermore, the cooling water flow can be controlled by a control valve (CV) linked to a Temperature Indicator Transmitter (TIT) to partially open or close the CV. Furthermore, a Flow Indicator Transmitter (FIT) can indicate the actual cooling water flow. **Figure 13** depicts the control system.

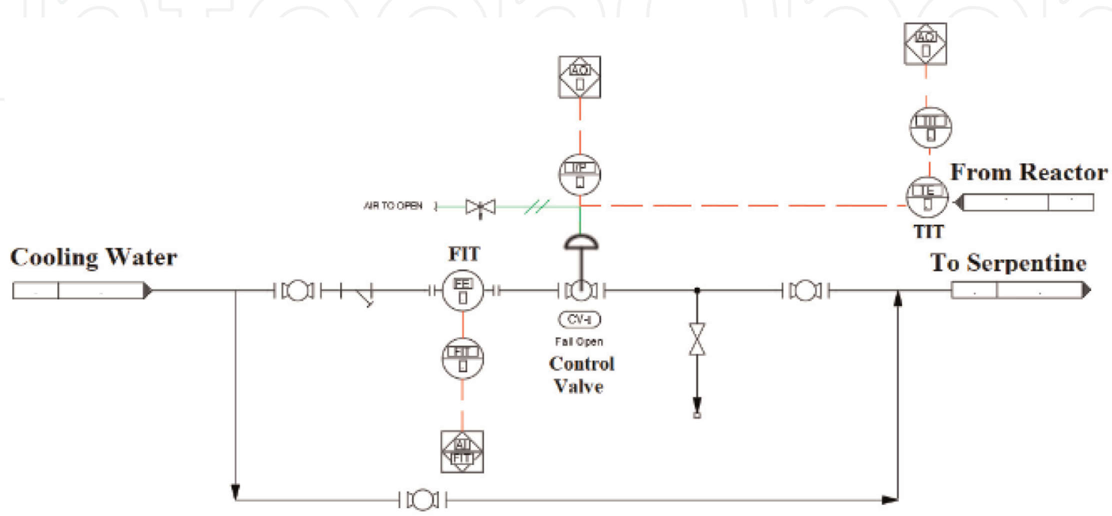

Figure 13.
Temperature control system.

Airflow system: The airflow is controlled by partially opening or closing a valve based on the flowmeter indication. Therefore, an error is added to the flow ratio since an operator performs the opening and closing of the valve, so the precision depends on how well an operator's eyesight is. The proposed solutions are: (1) Automate the airflow system through a control valve and two flow indicator transmitters. The control system aims to link the air's FIT with the biomass FIT, so the control valve will open or close to allow an airflow based on the amount of fed biomass and the established ER. **Figure 14** depicts the control system.

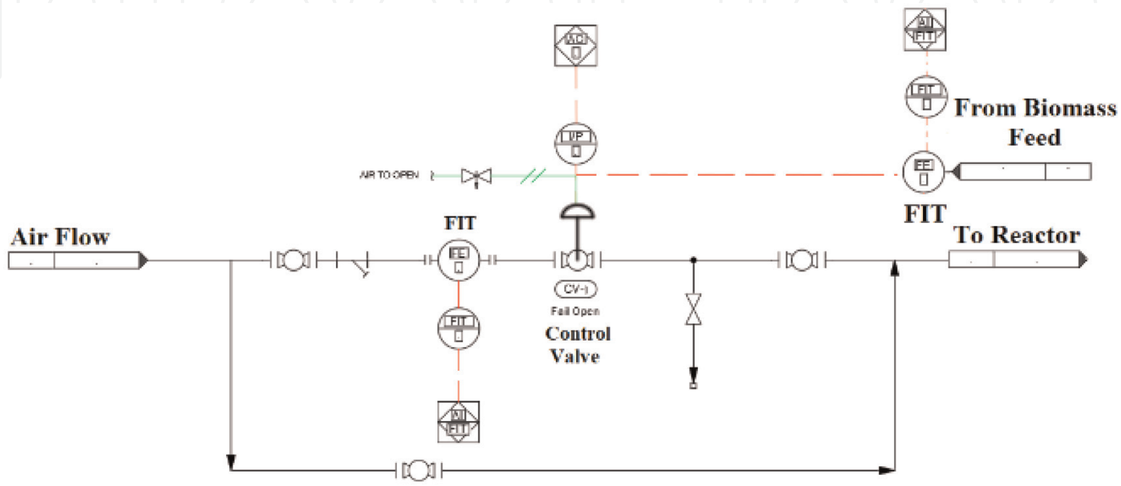

Figure 14.
Air flow control system.

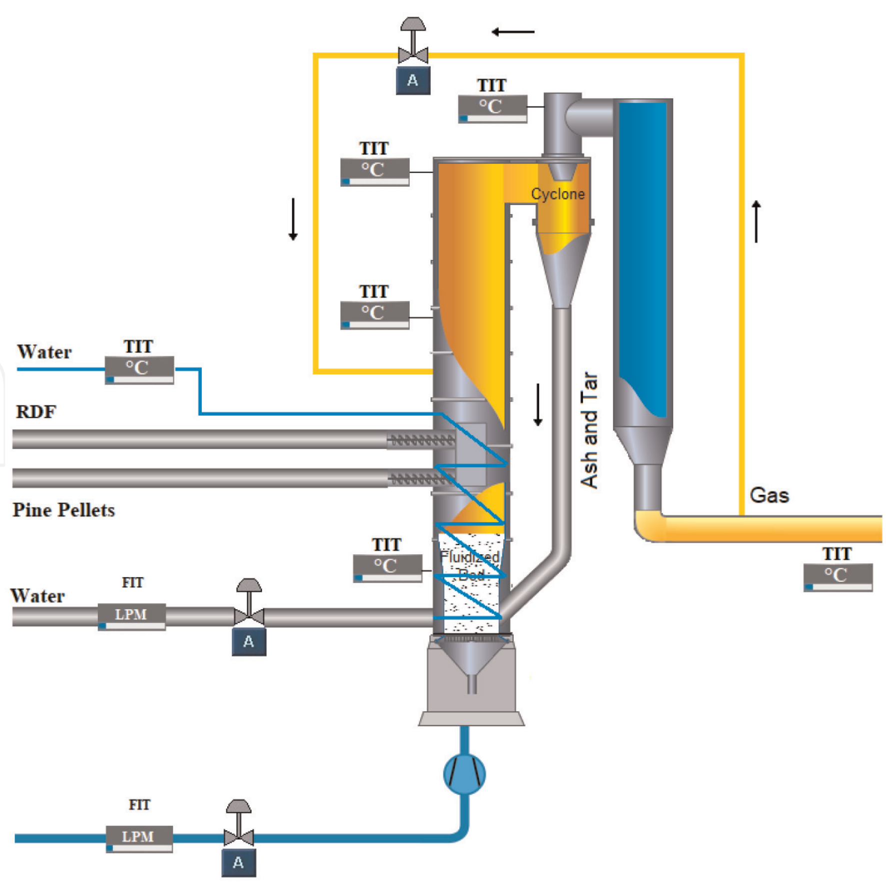

Figure 15.
PLC gasification process.

Biomass flow system: Several previous actions are necessary to control biomass flow, such as pretreating the biomass by establishing a homogeneous particle diameter range. This consideration is essential so that the feeder screw feeds the biomass homogeneously. (2) Another option is to change the mechanical feeding system to a pneumatic one, requiring biomass pretreatment and screening.

4.5 Control

The control phase sustains the Six Sigma DMAIC initiative through continuous monitoring to avoid the same problem [48]. So, a PLC can be installed to monitor and control the process as described in the improvement section. The PLC allows the operator to interact with the process without opening or closing valves to a particular flow, adding errors to the process. Furthermore, the PLC can save data by analyzing the process and promoting continuous improvement. **Figure 15** shows a typical PLC interface adapted to the gasification process.

5. Conclusion

In this chapter, the Six Sigma DMAIC methodology is used to identify causes of variance in the gasification process and suggest opportunities for improvement. In terms of the Equivalence Ratio (ER), the developed Failure Modes and Effects Analysis (FMEA) has a high-Risk Priority Number (RPN). This high figure is due to the method of feeding biomass, which significantly impacts airflow. In addition, the temperature has a high RPN value as well. This situation is due to the cooling mechanism of this device and the ER employed, which may be inaccurate. Finally, some ways are proposed to improve the air and biomass feeding and process cooling systems.

On the other hand, it demonstrated the process's stability and the synergy between RDF and biomass, resulting in enhanced gasification products. Furthermore, no slag, agglomeration, or defluidization phenomena were observed. Again, implementing the DMAIC methodology helped identify the source of variance and ways to enhance the overall process. Therefore, it has the potential to strengthen the gasification process, promoting the economic viability and environmental benefits of future and existing gasification plants.

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References

[1] Silva VBRE, Cardoso J. Overview of biomass gasification modeling: Detailed analysis and case study. In: Computational Fluid Dynamics Applied to Waste-to-Energy-Processes. Oxford, UK: Elsevier; 2020. pp. 123-149. DOI: 10.1016/b978-0-12-817540-8.00004-2

[2] Cardoso J, Silva V, Eusébio D. Techno-economic analysis of a biomass gasification power plant dealing with forestry residues blends for electricity production in Portugal. Journal of Cleaner Production. 2019;**212**:741-753. DOI: 10.1016/j.jclepro.2018.12.054

[3] World Bioenergy Association (WBA). Global Bioenergy Statistics. 2019. Available from: https://www.worldbioenergy.org/global-bioenergy-statistics/

[4] Cardoso J, Silva V, Eusébio D, Brito P, Hall MJ, Tarelho L. Comparative scaling analysis of two different sized pilot-scale fluidized bed reactors operating with biomass substrates. Energy. 2018;**151**:520-535. DOI: 10.1016/j.energy.2018.03.090

[5] Gov UK. Carbon Emissions Tax Consultation. London, UK: HM Revenue & Customs; 2020

[6] Power, The Shift from Coal to Biomass Is on in Europe. May 2018

[7] Gov UK, Carbon Emissions Tax Consultation. Jul 2020

[8] EnergyWatch, Portugal expedites coal plant phase-out to next year. Jul. 2020

[9] ClimateHomeNews. Portugal ends coal burning two years ahead of schedule. Jul. 2020

[10] Carbon Pulse, Analyst team sees EU carbon prices near €90 by 2030 as industrials forced to step up abatement. Oct. 2020

[11] ArgusMedia, EU ETS price €32-65/t under 2030 scenarios. Sep. 2020

[12] Bloomberg. EU carbon permits hits record 50 Euros on tighter pollution rules. May 04 2021. Available from: https://www.bloomberg.com/news/articles/2021-05-04/carbon-permits-hit-record-50-euros-on-tighter-pollution-rules [accessed Jun. 29, 2021]

[13] Investing.com. Carbon emissions futures price. Jun. 29, 2021. Available from: https://uk.investing.com/commodities/carbon-emissions [accessed Jun. 29, 2021]

[14] Dudek T. The impacts of the energy potential of Forest biomass on the local market: An example of south-eastern Poland. Energies (Basel). 2020;**13**(18):4985. DOI: 10.3390/en13184985

[15] Valmet, Biomass to energy solutions for high-efficient and sustainable power generation

[16] Daniell J, Köpke M, Simpson SD. Commercial biomass syngas fermentation. Energies. 2012;**5**(12) MDPI AG:5372-5417. DOI: 10.3390/en5125372

[17] GSTC. Gasification vs. incineration

[18] Alam MT et al. Co-gasification of treated solid recovered fuel residue by using minerals bed and biomass waste blends. Energies (Basel). 2020;**13**(8):2081. DOI: 10.3390/en13082081

[19] Pio DT, Tarelho LAC, Tavares AMA, Matos MAA, Silva V. Co-gasification of refused derived fuel and biomass in a pilot-scale bubbling fluidized bed reactor. 2020;**206**. DOI: 10.1016/j.enconman.2020.112476

[20] Nobre C, Longo A, Vilarinho C, Gonçalves M. Gasification of pellets produced from blends of biomass wastes and refuse derived fuel chars. Renewable Energy. 2020;**154**:1294-1303. DOI: 10.1016/j.renene.2020.03.077

[21] Poe WA, Mokhatab S. Process optimization. In: Modeling, Control, and Optimization of Natural Gas Processing Plants. Oxford, UK: Elsevier; 2017. pp. 173-213. DOI: 10.1016/B978-0-12-802961-9.00004-8

[22] Lei G, Zhu J, Guo Y, Liu C, Ma B. A review of design optimization methods for electrical machines. Energies. 2017;**10**(12):1962. MDPI AG. DOI: 10.3390/en10121962

[23] Mikel Harry PD, Schroeder R. Six Sigma the Breakthrough Management Strategy Revolutionizing the World's Top Corporations. New York, USA: Doubleday; 2000

[24] Chakrabarty A, Tan KC. The current state of six sigma application in services. Managing Service Quality. 2007;**17**(2):194-208. DOI: 10.1108/09604520710735191

[25] Virender Narula SG, Narula V, Grover S. Six Sigma: Literature review implications for future research. International Journal of Industrial Engineering & Production Research. 2015;**26**(1):13-26. DOI: 10.1016/j.ijproman.2010.01.006

[26] Maurus S. Lean Six Sigma in Versicherungen. In: Handbuch Versicherungs Marketing. Berlin Heidelberg: Springer; 2019. pp. 505-531. DOI: 10.1007/978-3-662-57755-4_29

[27] Mikel J. Harry Harry's contributions to Six Sigma

[28] Gibbons PM, Kennedy C, Burgess S, Godfrey P. The development of a value improvement model for repetitive processes (VIM): Combining lean, Six Sigma and systems thinking. International Journal of Lean Six Sigma. 2012;**3**(4):315-338. DOI: 10.1108/20401461211284770

[29] Sreeram TR, Thondiyath A. Combining lean and Six Sigma in the context of systems engineering design. International Journal of Lean Six Sigma. 2015;**6**(4):290-312. DOI: 10.1108/IJLSS-07-2014-0022

[30] Garza-Reyes JA, Kumar V, Chen FF, Wang YC. Seeing green: Achieving environmental sustainability through lean and Six Sigma. International Journal of Lean Six Sigma. 2017;**8**(1):2-6. DOI: 10.1108/IJLSS-01-2017-0005

[31] da Silva FF, Filser LD, Juliani F, de Oliveira OJ. Where to direct research in lean Six Sigma?: Bibliometric analysis, scientific gaps and trends on literature. International Journal of Lean Six Sigma. 2018;**9**(3):324-350. DOI: 10.1108/IJLSS-05-2017-0052

[32] Li N, Laux CM, Antony J. How to use lean Six Sigma methodology to improve service process in higher education: A case study. International Journal of Lean Six Sigma. 2019;**10**(4):883-908. DOI: 10.1108/IJLSS-11-2018-0133

[33] Petrenko Y, Denisov I, Koshebayeva G, Biryukov V. Energy efficiency of Kazakhstan enterprises: Unexpected findings. Energies (Basel). 2020;**13**(5):1055. DOI: 10.3390/en13051055

[34] Li P, Jiang P, Zhang G. An enhanced DMAIC method for feature-driven continuous quality improvement for multi-stage machining processes in one-of-a-kind and small-batch production. IEEE Access. 2019;**7**:32492-32503. DOI: 10.1109/ACCESS.2019.2900461

[35] Roger B. Lean Six Sigma Business Transformation for Dummies. New Jersey, USA: John Wiley & Sons, Ltd.; 2014

[36] Hanafi NA, Tan OK, Goh CG. Categorization of lean six sigma tools and techniques based on DMAIC framework. Journal of Information System and Technology Management. 2019;**4**(13):1-12. DOI: 10.35631/JISTM.413001

[37] Noori B, Latifi M. Development of Six Sigma methodology to improve grinding processes: A change management approach. International Journal of Lean Six Sigma. 2018;**9**(1):50-63. DOI: 10.1108/IJLSS-11-2016-0074

[38] Praveen G. Chapter Two. Six Sigma —An Overview. in Six Sigma Business Scorecard Ensuring Performance for Profit. New York, USA: McGraw-Hill, Ed.; 2004. pp. 17-39

[39] B. Carreira, Lean Six Sigma That Works a Powerful Action Plan for Dramatically Improving Quality, Increasing Speed, and Reducing Waste. NY, USA: AMACOM Publisher; 2006.

[40] Wasage C. Implementation of Six Sigma projects in fortune 500 companies. Journal of Modern Accounting and Auditing. 2016;**12**(4):208-216. DOI: 10.17265/1548-6583/2016.04.002

[41] Srinivasan K, Muthu S, Devadasan SR, Sugumaran C. Enhancing effectiveness of shell and tube heat exchanger through six sigma DMAIC phases. Procedia Engineering. 2014;**97**:2064-2071. DOI: 10.1016/j.proeng.2014.12.449

[42] Krishna Priya S, Jayakumar V, Suresh Kumar S. Defect analysis and lean six sigma implementation experience in an automotive assembly line. Materials Today: Proceedings. 2020;**22**:948-958. DOI: 10.1016/j.matpr.2019.11.139

[43] Bloj M-D, Moica S, Veres C. Lean Six Sigma in the energy service sector: A case study. Procedia Manufacturing. 2020;**46**:352-358. DOI: 10.1016/j.promfg.2020.03.051

[44] Costa T, Silva FJG, Ferreira LP. Improve the extrusion process in tire production using Six Sigma methodology. Procedia Manufacturing. 2017;**13**:1104-1111. DOI: 10.1016/j.promfg.2017.09.171

[45] Pask F, Sadhukhan J, Lake P, McKenna S, Perez EB, Yang A. Systematic approach to industrial oven optimisation for energy saving. Applied Thermal Engineering. 2014;**71**(1):72-77. DOI: 10.1016/j.applthermaleng.2014.06.013

[46] Kane J, Dupont EI. Using Six Sigma to drive energy efficiency improvements at DuPont

[47] Silva V et al. Multi-stage optimization in a pilot scale gasification plant. International Journal of Hydrogen Energy. 2017;**42**(37):23878-23890. DOI: 10.1016/j.ijhydene.2017.04.261

[48] C. Sarah and S. S. Academy, The Black Belt Memory Jogger, Second. Massachusetts, USA: Goal/QPC; 2016