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Evaluating the Integration of Sustainability Concepts in Plant Design Projects within the Chemical Engineering Programme at Universiti Malaysia Sabah

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Abstract: This paper presents a brief evaluation of the Capstone Chemical Engineering Design Courses, Plant Design Project I & II, offered in the fourth and final year of undergraduate study at Universiti Malaysia Sabah. One main focus is to identify the elements of sustainability as concepts delivered in the courses to align with United Nations' Sustainability Goals and the latest Engineering Accreditation Standard (2024). Though the concept of sustainability is not explicitly measured, it is found to be substantially linked to the criteria for selecting alternative designs and optimisation of the final design in the project. Strengths and weaknesses of the courses are discussed, with reference to five institutions' concepts and pedagogy on sustainability, along with recommendations for improvements in the courses in the near future. According to a study by one of the institutions, the subject of process control requires particular attention when designing a plant, as it is highlighted by professional engineers as pivotal in optimising plant operation for sustainability.

Keywords: sustainability, capstone, process, design, chemical engineering, pedagogy

1. Introduction

In this brief evaluation, it is presumed that the reader is familiar with the Outcome-Based Education (OBE) terms in the EAC Engineering Programme Accreditation Standard and Washington Accord documents. In the latest 2024 standard [1], there are two explicit references (PO2 and PO6) to sustainability in the 11 programme outcomes and one (PO3) where the elements listed are clearly on sustainability. The mappings of the teaching and learning parameters namely: programme education outcomes, knowledge profile and complex problem solving and complex engineering activities, are in the syllabus, but they shall not be presented here, as they are not the focus of this evaluation.

The purpose is to illustrate how sustainability is embedded throughout the fourth and final year design project courses of chemical engineering programme at Universiti Malaysia Sabah as of July 2024, in compliance with the EAC 2020 Standard. The treatise begins with the introduction of the core concepts applied in the courses developed since 2001 and then compared with existing practices elsewhere.

Relevant information was drawn from five sources domestically and internationally, namely: 1) Heslop [3] describes typical design projects and shows the pedagogy on integrating the United Nations Sustainable Development Goals (SDG) in the course at University of Strathclyde; 2) At University College London, the chemical engineering capstone design project promotes sustainability both in the project and in the course [4]; 3) Pauzi and Kasim [5] reviewed several project-based learning models and proposed a combination of these models to enhance the learning of complex problem solving through design projects at Universiti Malaysia Perlis; 4) Fitzpatrick et al. [6] concluded that sustainability should provide guidance in influencing the design decisions rather than merely being assessed after a design is completed, in the design projects at University College Cork of Ireland and 5) Process or operation optimisation, which should play a significant role of design project's sustainability, was ranked the highest among concepts critical to systems-and-control professionals working in various industries, including biotechnology, pharmaceuticals, petroleum and petrochemicals, chemicals, consumer products, and process control, and noted by Alford and Edgar [7] of University of Texas in Austin to be omitted in many process control courses. We shall describe the implementation of the courses in terms of delivery including the coordination of the projects and assessment.

2. Core Concepts

The review has been conducted by utilizing four basic concepts or values that undergird the plant design courses in the coordination of activities, in the format and quality of outputs, and in the assessments. The teaching and learning approach of the courses, from past sessions to the most recent, is evaluated through these concepts.

2.1 Choices – qualitative and quantitative evaluation

Design is not merely about sizing equipment, vessels and pipelines. It requires the exercise of judgement after analysis. In the language of Washington Accord's complex problem solving scale, it often requires an in-depth knowledge of fundamentals (WP1) and weighing between multiple conflicting requirements (WP2), involves infrequently encountered issues (WP4), tackles problems not encompassed by standards and codes of practice for professional engineering (WP5) and can involve diverse groups of stakeholders with widely varying needs, which can be complicated in real situations (WP6). Students make choices when carrying out plant design that involve technical and non-technical constraints in reaching the design objective. As an example, typically a main objective is the production rate, which the students must decide based on market survey, geographical considerations and competition.

2.2 Sustainability – the paramount requisite of selection

The overall aim of the UN's SDGs is sustainability, where eleven (11) of the seventeen (17) goals have the word 'sustainable', and the latest EAC Standard for Engineering Accreditation (2024) has two PO's with the word 'sustainable' and one contains elements strongly linked to sustainability. This is also the paramount requisite in the Plant Design Project, in the areas of economics, environment and society. Sustainability in economics is instinctively essential since a profit must be made for viability. The areas of environment and society are often governed by laws and regulations and influenced by the sentiments of the stakeholders, or people with interest in the project (WP6).

2.3 Contingency, Exigency and Allowance for Future Expansion, Retrofitting and Renovation (WP4)

In a fast-changing world, the unforeseen occurs with increasing frequency. Incorporating safety features in design is required by law under the OSHA Act 514 Part V:20. These should be allowed for to prevent any interruption to any loss of life, or the plant's operation or damage to the environment and should be included in design. There will be times when emergency measures have to be taken and thoughtful preparations should be made for these. The life of a chemical processing plant is dynamic and the design should be flexible enough to retrofit newer technologies onto the existing facility and accomodate expansion if the market grows. Equipment failure rate prediction is necessary to estimate how many backup units are required. To allow for backup equipment, designers must consider how much extra room is required in a plant layout. Backup pumps and the use of standard and modular process equipment are encouraged to prepare for such eventuality.

2.4 Professionalism and Ethics (PO8)

Professionalism and ethics in this project are about how to carry out design in a professional and ethical manner [8], not about tackling ethical issues in the project, which belongs to the category of design constraints, i.e. to design in such a way without violating them. An example of such an ethical conundrum is to decide whether to import cheaper feedstock harvested from a source with reputation of forced labour or to obtain it from a reputable source but at a higher price or with longer delivery times. This would be a complex problem concerning WP2 and WP6. However, this kind of ethical problem does not occur in every project which is why it is exempted from assessment. Firstly, the design should be carried out professionally with reasonable assumptions that are justified, e.g. a reaction conversion rate of 0.8 based on an existing plant, calculation or reference in technical literature, or assuming zero heat loss with good insulation wrapped around a heated vessel. Secondly, due diligence is required to ascertain the validity of data obtained [7]. Thirdly, traceability of information and data must be ensured. Fourthly, the calculation methods and results should be double-checked by an independent means, if available. Fifthly, standards and codes are mandatory where applicable. Finally, minutes of group meetings should document decisions made, their rationale, and any follow-up actions.

Broadly, the concepts can be represented by an onion-structured diagram in Figure 1. The interrelation of these concepts is why Pauzi and Kasim [5] viewed project-based learning in capstone design projects as an excellent means of preparing the graduates for professional practice. The mapping of the concepts with the EAC programme outcomes is presented in Table 1. A comparison between UMS and other institutions, based on their published articles, is shown in Table 2. Generally, most institutes of higher learning include these concepts in one way or another similar to UMS.

Figure 1. Four basic concepts undergirding the course

Table 1. Mapping of core concepts in the course to programme outcomes

Concept	Programme Outcome											
	1	2	3	4	5	6	7	8	9	10	11	12
Sustainability		√	√			√	√				√	
Contingency and Exigency			√			√	√					
Professionalism and Ethics								√	√	√	√	√
Design Choices	√	√	√		√				√	√	√	

Table 2. Comparison with other institutions in addressing the core concepts

Institution	Sustainability		Professionalism and Ethics	Modularity for Expansion / Contingency and Exigency	Design Evaluation of Choices
	Influence Design	Assessed after design			
University of Strathclyde	Yes	Yes	Not stated	Not stated	Yes
University College London	Yes	Yes	Not stated	Yes	Yes
Universiti Malaysia Perlis	Not stated	Yes	Yes	Not stated	Yes
University College Cork of Ireland	Not stated	Yes	Not stated	Yes	Yes
University of Texas in Austin	Yes	Yes	Yes	Yes	Yes
Universiti Malaysia Sabah	Yes	Yes	Yes	Yes	Yes

3. Discussion

3.1 Sustainability in the Pedagogy

At Universiti Malaysia Sabah (UMS), chemical engineering undergraduates are introduced to design concepts and practices in the second year, starting with designing individual process equipment, and in the third year with process design, where pinch analysis is applied, and simulation is required to reach a solution. The overall capstone design project course outcome is to produce plant designs that are sustainable in process economics, in the management of the environment and in channeling optimal benefits to society. To reach this goal, programme outcomes of the Engineering Accreditation Council Standard 2020 have been applied as criteria in eleven (11) of twelve (12) different outcomes. The project is broken down into five (5) milestones over two semesters with a total credit hour of 7. The final year comprises mainly project-based courses, namely Capstone Plant Design and Research projects, and is topped up by elective and non-fundamental courses, so that the study time is less than the activity time, and time management becomes a major challenge. Students are assigned into groups of five and lecturers supervise one group each with weekly or biweekly meetings that are minuted (PO11).

Selection of topics for each plant is based on the mandatory inclusion of a reactor. A proposed plant topic that does not contain a reactor as a process stage is disqualified and will be rejected. To encourage students in applying process simulation software, novel plants that cannot be simulated are also ruled out. At present most plants are continuous operation and the minority are designed in batch or semi-batch modes.

After receiving a topic, it is too onerous for each group to design from scratch the production process of the entire plant. Designs of process evaluation, from feedstock to the final product, and the technologies (equipment types) to bring about the processing at every stage, are sourced from existing plants, patents or journals. If the production process is an established one, then the process design may not require much modification. The processes are often simplified and modified since every process is not exactly appropriate for conversion to the final product of the specification.

The activities required to achieve Milestones (MS) 1 through 5 are broken down into approximately linear procedures. In Semester 1, MS1 to MS3 focus on process and plant equipment analyses exercises; no design work takes place during this phase. In Semester 2, MS4 involves detailed process and equipment design, while MS5 focuses on and design integration of the plant through critical review.

MS1 is the feasibility study on the background, market survey, competition, current technology of process and equipment types (Figure 2). The groups determine product specification and plant specification based on the market survey and commercial rivalry, shortlist alternative processes qualitatively and quantitatively, where design objectives and design constraints are frequent examples of conflicting requirements (WP2). The report highlights foreseeable environmental, health and safety issues, regulations, legislation, protocols relevant to the proposed plant will be tackled or avoided, It also includes an economic analysis with estimated payback time and return on investment. The shortlisting of process alternatives is carried out by comparing them based on profitability, efficiency, waste generation, low or no toxic discharge, cost-effectiveness, and the interests of various stakeholders. This ties in with utilising the concept of sustainability in making design decisions, which Fitzpatrick et al. [6] remarked as the ideal application of the concept, rather than merely assessing whether a design is sustainable after it is completed. Heuristics are available as tools for the elimination of the alternatives by assisting in reaching the objective while meeting the constraints; however, experience with the students' past output shows these are rarely used and the simple tabulation of characteristics are the preferred means in sifting out the best option. At the end of MS1, they will recommend the plant to be designed, with the sustainability elements satisfied above other options. It is obvious that the topics assigned to the groups are all inherently feasible, but the exercise in MS1 is to demonstrate convincingly that it is feasible through the analysis. The duration for achieving MS1 is five weeks.

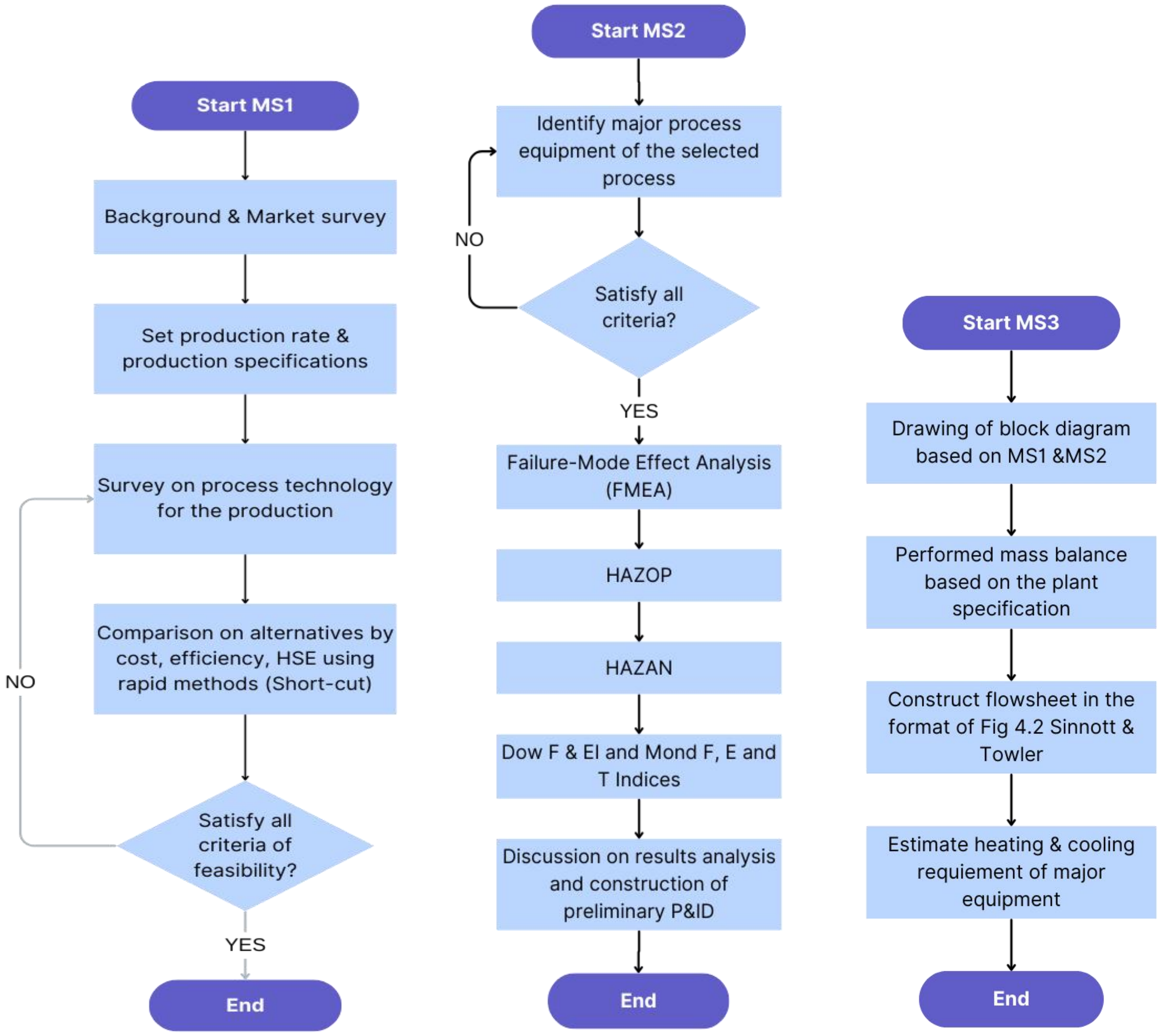

Figure 2. Procedural steps of Milestone 1 to 3

In MS2, the process and equipment of the plant are assumed with the technology selected. The groups set out to identify the major equipment, which must have reaction, heat (2-phase) or mass transfer along the primary production route. Sophisticated plants can be simplified to 5 major equipment, i.e. equipment that process the materials along the production route. If a plant has too few major equipment, some ancillary equipment can be upgraded, e.g. a boiler or condenser of a distillation column. Failure-Mode Effect Analysis (FMEA) has recently been introduced as a pre-requisite to the rigorous HAZOP/HAZAN to detect and mitigate potential hazards. Supplemental analyses are encouraged like Dow Fire & Explosion Index and ICI Mond Fire, Explosion and Toxicity Indices. Each group will make comments and recommendations for each equipment with respect to the severity of the hazards identified and the method of mitigation, which instill the concepts of contingency and exigency in their design. The results of FMEA, HAZOP and HAZAN are used to construct a preliminary piping and instrumentation diagram (P&I D). The concept of sustainability applies in evaluating whether the proposed piping and instrumentation is feasible, e.g. logical control and appropriate types and numbers of sensors. The duration to reach MS2 is five weeks.

Moving on to MS3, the major equipment identified in HAZOP activity of MS2 are performed mass balance based on the plant specification. Flowrate and composition values are usually lifted from the information sources on the process selected. Because these are preliminary guesses and estimates, they do not necessarily obey thermodynamics in terms of feed composition and outlet composition; therefore, the energy balance is rarely satisfied and is not a requirement of MS3. However, the groups can estimate the quantity of heat transfer required. Process simulation software is used to verify the manual calculation of the mass balance. The balance achieved is very good in most cases, with a discrepancy of less than 1 per cent between inlet and outlet and between manual and software calculations. The flowsheeting format follows the industry standard as given in Sinnott and Towler [9] and the template explained in the lecture notes. The concept delivered here is professionalism and ethics (PO8). The duration to reach MS3 is four weeks.

In the detailed process equipment design stage, MS4 (Figure 3), the students are carrying out design on their particular major equipment as identified in MS2, using the conditions set out in MS3. Design objectives and design constraints are defined. If the objective can be achieved by all alternatives, similar criteria of selection as in MS1 are used with minor variations. For example, costing will be compared between different design alternatives for selection for economic sustainability, rather than process economics compared between with tax incentives or without incentive, and energy efficiency for resource sustainability, or the least effluent waste discharge for environmental impact sustainability. However, it is found that this kind of comparison is rarely practised by the students as their reports merely show quick elimination of alternatives by qualitative or short-cut methods, which is acceptable at MS1 but not at MS4. Then the detailed design calculations are just for sizing. Admittedly, at MS4, the complexity involving too many unknowns and unfamiliar situations due to the lack of data has compelled some students to resort to applying short-cut methods only for sizing and analyzing. Too few are doing rigorous comparisons of, say, for a distillation column, reflux ratio or number of stages between bubble cap and sieve tray. It is expected of each student to draw up a table comparing each of these criteria in terms of technical performance, cost (capital and operating), efficiency and HSE, to make informed decisions in selecting the optimized design. After calculations, only some managed to double-check their results mostly by referring to the constraints when alternative methods of estimating the sizes are available in textbooks or literature. Uncertainty is also never stated in any report to date, the importance of which should be communicated to the students. In the mechanical design of their process equipment, students are compelled to apply standards and codes such as BS EN 13445 for calculating and specifying the dimensions and shapes. The finalized design information and data are to be presented in templates of data specification sheet for ease of communication in the industry. All this is to inculcate professionalism and ethics into their routine (PO8) of making choices in design. Mechanical drawings conforming to standards and preferably drawn by software such as AutoCAD are mandatory for the overall dimensions of the major equipment, where the physical dimensions will be appraised to determine whether they can reasonably fit into the plant site (Contingency and Exigency).

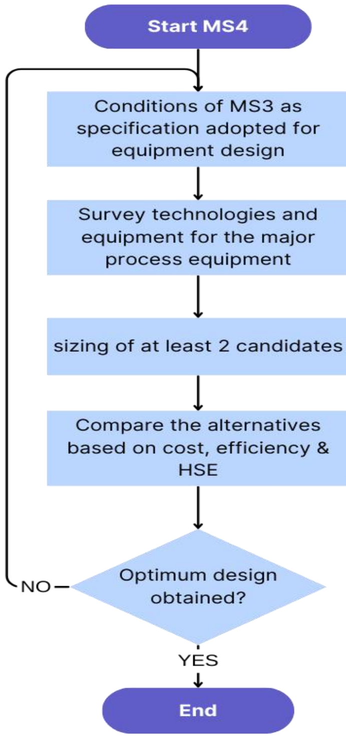

Figure 3. Procedural steps in Milestone 4 Detailed Process Equipment Design

Process control design leading to a P & ID is found to be wanting, as lamented by Alford and Edgar [7] for the lack of attention of this subject in the programme. Assessors frequently found the P & ID presented in the reports to be disappointing; students do not see that control is used to maintain the set points of the desired production rate or quality, and do not know how to design per equipment or how to look at plantwide process control. This will be an item for continual quality improvement (CQI) of teaching and learning the subject of process control in the programme.

Inclusion of Environmental Impact Assessment EIA at MS4 has been trimmed to estimating carbon and water footprints and waste discharge, but this is hardly carried out, either due to lack of knowledge or lack of time. These calculations do not require complex analysis to obtain results. The duration to reach MS4 is seven weeks.

In the final milestone phase, MS5, as shown in Figure 4, each group performs critical self-review of the progress thus far, to instill lifelong learning habit (PO12), focusing on improvements under the following headings:

(a) Risk Assessment Safety Strategies (Cost comparison for each strategy and choice);
(b) Environment Impact Assessment – carbon dioxide emission (e.g. quantity of carbon emission/kg product from fuel burnt, toxic gases and effluent footprint, water footprint), where Climate Change summits and international protocols for carbon footprint reduction targets by signatory countries are referred to;
(c) Energy efficiency (e.g. kg product / kWh spent, kg product / mass of steam used), energy audit (Location of the streams in the plant, types of energy used), and Pinch Analysis;
(d) Integration of plant with respect to mass and energy balances, operating conditions. Consecutive process operations should have temperatures, pressures and flowrates that match

each other at the connections: outlet from block 1 should match the inlet of block 2 and so forth, where the final flowsheet should show integration of plant equipment, e.g. flowrates between neighbouring equipment should match. Input and output data should be shown around equipment symbols;
(e) Plant layout with respect to modularity of processes and equipment, e.g. expandability, back-up equipment, ease of retrofitting, ease of operation – personnel qualification, training required and number of shifts. Logistics – start-up, shut-down, feedstock supply chain, storage and distribution of intermediate and final products should also be considered. They should allow for the effect of these factors on plant layout design;
(f) Project economic evaluation for the entire plant under several scenarios. A scenario must be significantly different in magnitude and quality from another, e.g. alternative design, tax incentives, inflation, doubling or halving the capacity, change of feedstock, change of product specification, market shift in demand, and so on.

Items (a), (b), (c) and (f) come under the concept of sustainability, (d) is professionalism and ethics, and (e) is contingency and exigency.

Each member of a group undertakes to review and improve the aspect of design for one of the headings. The duration to reach MS5 is four weeks, and the last three weeks of the semester are allocated for viva preparation and execution, conducted online for the convenience of industry assessors. In the most recent viva, one of the industry assessors had participated remotely from an offshore rig. In the discussion and conclusion, the group can add whether they have implemented or rebutted the suggested improvement of any suggestion, recommendation or advice from industry. The experience of marking MS5 reports shows that in part (a) costing comparison of safety strategy alternatives is seldom carried out for sustainable safety, and in part (c) pinch analysis is presented but the various efficiency indicators suggested in the guidelines are rarely calculated. In contrast to MS4, carbon and water footprints and waste discharge both scheduled and unscheduled, are satisfactorily reported in MS5.

An exercise that has not been undertaken by any plant design project at UMS to date is the Life Cycle Analysis (LCA), which has received favourable feedback comments from students at University College London [4]. Incorporating lifecycle carbon footprint for the production of a chemical can be considered for future MS5 exercises with the aid of software package [6]. To realise the optimisation of parts (a), (b) and (c), fine tuning of process control design will play an important role of process or operation optimisation [7]

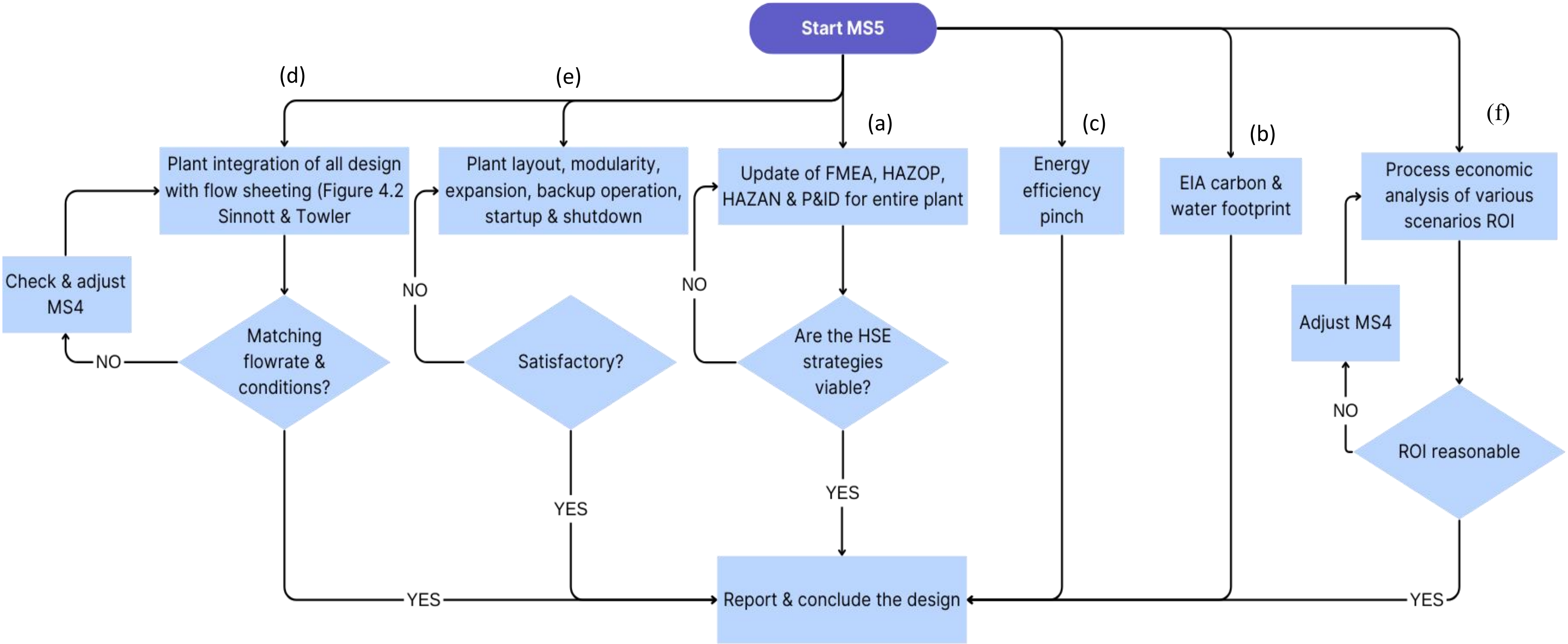

Figure 4. Procedural steps in Milestone 5 Plant Integration and Optimisation

The assessment methods and weightings are detailed in the syllabus; only the implementation will be described here. For project reports MS1, MS2, MS3 and MS5, the marks obtained are group-based, while MS4 report is assesed individually. Viva at MS1 is conducted to steer the direction of the groups to ensure they receive early feedback to correct any fundamental errors, with marks awarded the group. In contrast, MS4 and MS5 viva marks are awarded to individuals. Peer assessment is currently the only gauge of leadership and team work (PO9). All project assessment is guided by rubrics, and industry assessors are invited to critique the work and provide valuable feedback from an industry perspective. A theory test is given for each semester and earns individual merit.

If viewed overall, MS1 majors on the concept of Sustainability, MS2 on Contingency and Exigency, MS3 on Professionalism and Ethics, while MS4 and MS5 have to deal with all four concepts simultaneously. Students who have conscientiously worked through the plant design projects I & II are well equipped to face the industry demands, having had a taste of its reality in complexity, and are future-proofed in their career prospects. While the course is substantially aligned with UN's SDG's, there remains room for improvement in the design project teaching and learning model to further enhance the students' ability to solve complex problems,as emphasized by Pauzi and Kasim [5].

3.2 Is the Pedagogy in the Capstone Design Courses Sustainable at UMS?

The concept of sustainability extends to the education vehicle to make these courses a great learning experience, a holistic approach espoused by UCL[4]. In terms of student learning time (SLT), it has been accounted for at the syllabus design stage. The quantity of man-hours required for supervision appears reasonable, with regular supervisor-group meetings and report reports assessment deadlines being met by the programme grade moderation deadline in August 2024. The number of industry assessors willing to carry out viva assessment is sustainable because it is carried out online.

4. Conclusions

Four core concepts have been identified and embedded in the Chemical Engineering Plant Design Project at Universiti Malaysia Sabah. While sustainability concept is not explicitly assessed, its elements can be seen to be taught and assessed in nearly all milestones of the project, aligning with the SDG's issued by the United Nations. LCA may be considered as an added exercise in MS5 in future, and process control design should be emphasized. Demonstration of professionalism and ethics in the design report needs to be communicated to the students. The substantial content of sustainability empowers the students to blend well with industry and future-proof their careers.

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Conflicts of Interest

The authors declare no conflict of interest.

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