CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761129

Systematic Framework for Design of Biomass Energy Systems: Addressing Criticality via Redundancy Allocation

Viknesh Andiappan[a,*], Michael Francis D. Benjamin[b], Raymond R. Tan[c], Denny K. S. Ng[d]

[a]Energy and Environmental Research Group, School of Engineering, Taylor's University, Lakeside Campus, No. 1 Jalan Taylor's, 47500 Subang Jaya, Selangor, Malaysia.
[b]Research Center for the Natural and Applied Sciences, University of Santo Tomas, España Blvd., 1015 Manila, Philippines
[c]Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
[d]Department of Chemical and Environmental Engineering/Centre of Sustainable Palm Oil Research (CESPOR), The University of Nottingham Malaysia Campus, Broga Road, Semenyih 43500, Malaysia
VikneshAndiappan.Murugappan@taylors.edu.my

A biomass energy system (BES) consists of highly integrated process units within a network. Via process integration, such system can achieve higher thermodynamic efficiency levels and economic performance as compared to conventional stand-alone systems. However, such benefits may not be realised if an energy system is not equipped to cope with failure of its component process units. A failure event can cause "ripple effects" to propagate throughout the BES and disrupt its overall performance. To address this, designers often allocate additional or redundant process units for the entire BES. However, this approach requires high capital investment; thus, redundancy allocation for the entire BES would not be possible. An appropriate resolution for this issue would be to identify the most critical process unit in the BES prior to allocating equipment redundancy. In this respect, this work presents a decision making framework for designing BES by addressing criticality of process units via redundancy allocation. The first stage of the framework consists of criticality analysis approach based on input-output (I-O) analysis. The criticality analysis identifies the most crucial process unit by quantifying the effect of a component's disruption within the BES. After identifying the most critical process unit, the second stage of the framework allows designers to systematically allocate equipment redundancy based on their budget restrictions via *k*-out-*m* system modelling or process intensification. To demonstrate the proposed framework, a palm-based BES case study is solved.

1. Introduction

Biomass energy systems (BESs) are utility systems which produce heat, power and cooling simultaneously from biomass. With such efficient use of biomass, a BES on-site would be beneficial as it reduces the importation of power and fuel (from large distances), reduces environmental impact, and improves local power reliability (Stoijkov et al. 2011). However, such benefits may not be realized if a BES is not sufficiently equipped to cope with an event of failure (e.g., preventive maintenance, equipment breakdown). Since a typical BES contains a network of interconnected equipment, an event of failure would disrupt the overall system performance. In this respect, it is arguable whether an energy system design is suitable for keeping a desired level of reliability in meeting energy demands. A common way of addressing such issue is by implementing redundancy allocation (RA). RA is a strategy of employing additional number of equipment connected in parallel to perform the same function, with the intention of achieving higher system reliability. Optimization studies have been employed to address the RA in energy systems. For instance, Olsommer et al. (1999) proposed a methodology to optimize the design and operation of a co-generation system subject to different operating scenarios. The methodology also performs a reliability analysis via an automated program and determines all the possible failure modes upon defining the optimal system. Frangopoulos and Dimopoulos (2004) then extended the previous work, by using the same steps but all within one optimization procedure. In their contribution, a search routine using genetic algorithm first proposes a design for which reliability analysis is carried out, generating all possible failure scenarios and calculating penalties whenever the demands are not fully met. The corresponding investment and operating costs are then compared with the designs automatically generated from the search, until a near-optimal solution is found. Besides, Aguilar et al. (2008) presented a framework to address reliability issues in the design and operation of a utility system. In their work, a robust optimization framework was presented to tackle grassroots and retrofit problems. In addition, the presented framework determines the RA for the system based on different time horizons and failure scenarios. Voll et al. (2012) presented a framework on automated superstructure generation and optimization of a trigeneration system based on different demands, available technologies, equipment redundancy and topographic constraints. Recently, Andiappan et al. (2015) developed a model for the synthesis of centralized trigeneration hubs incorporating reliability aspects. A subsequent work extended this approach to consider sizing and redundancy in consideration of operational aspects (Andiappan and Ng, 2016). On the other hand, Benjamin et al. (2015a) proposed a metric called criticality as a measure of the extent to which a component in a highly integrated system acts as a source of disruption to a network using input-output (I-O) analysis. In the original work, it was used for the analysis of bioenergy parks (Benjamin et al., 2015a); a subsequent paper extended the approach to consider multiple disruption scenarios defined by probabilities of occurrence (Benjamin et al., 2015b). More recently, Benjamin et al. (2016) used a process graph approach for criticality analysis in bioenergy parks.

The aforementioned contributions focused on allocating redundant process units for an entire system. However, this approach requires high capital investment, making overall system RA less favourable. In this paper, an integrated framework is proposed for planning system redundancy based on criticality analysis. This new approach combines the criticality analysis concept (Benjamin et al., 2015a) with an engineering intervention (Andiappan and Ng, 2016) to allow the results of the prior analysis to be used to make design adjustments. Criticality analysis can identify the most critical process unit which will affect the entire operation of the system. Based on the identified critical process unit, equipment redundancy allocation can be done based on the process owner budget restrictions. Via the proposed framework, significant lower investment is needed while maintaining the ability of the system to fulfil the process requirement.

2. Problem Statement

Criticality analysis is developed by Benjamin et al. (2015a) in order to identify the most critical unit or component plant in an integrated energy system such as a BES. This approach is based on quantifying the effects of a disrupted or inoperable component (e.g., BES process unit) to its corresponding final output (e.g., product stream). In this work, the problem statement is as follows. The BES is composed of *n* number of process units, with each unit is characterized by a scale-invariant material and energy balance ratio. For each scenario, one particular BES process unit is assumed to be disrupted and affects its corresponding final output. The reduction in the final output is then determined via I-O analysis to determine which is the most crucial in the BES with respect to the magnitude of the disruption consequence. To address the criticality of the bottleneck process unit, a redundancy allocation approach was employed. The approach employed in this work is the *k*-out-of-*m* modelling, adapted in Andiappan et al. (2015). This approach systematically allocates redundancy based on the reliability of the critical process units subject to a minimum reliability level..

3. Framework

This section presents a systematic framework that addresses criticality in BES design via redundancy allocation (RA). As shown in Figure 1, the proposed framework begins with criticality analysis (Benjamin et al., 2015a). In criticality analysis, the most critical unit in a BES is identified. This is achieved by quantifying the effects of a disrupted or inoperable process unit to its corresponding final output (e.g., product stream). The quantification of the mentioned effects is denoted by a criticality index. The process unit with the highest criticality index is deemed the most crucial unit in the BES. Once the most critical unit is determined, the subsequent tasks comprises of two possible design modifications. These modifications include (but not limited to) RA (Andiappan et al., 2015) and process intensification (Stankiewicz and Moulijn, 2000). RA increases the reliability of a process unit via additional or back-up facilities. The required RA is determined via *k*-out-of-*m* system modeling (Coit and Liu, 2000) as shown in Eq(1) – (5).

$$\sum_{n=1}^{N} z_{jn}\mathrm{F}_{jn}^{\mathrm{Design}} \geq \sum_{w=1}^{W} a_{wj}\ x_j \qquad \forall j \qquad (1)$$

$$R_{jn}\left(m_{jn} \geq z_{jn}\right) = \sum_{k=z_{jn}}^{m_{jn}} {}^{m_{jn}}C_k \left(\mathrm{P}_{jn}\right)^k \left(1-\mathrm{P}_{jn}\right)^{m_{jn}-k} \qquad \forall j \forall n \qquad (2)$$

$$R_j = \sum_{n=1}^{N} R_{jn} I_{jn} \qquad \forall j \qquad (3)$$

$$z_{jn} \leq \mathrm{M} \times I_{jn} \qquad \forall j \forall n \qquad (4)$$

$$R_j \geq \sum_{n=1}^{N} \mathrm{R}_{jn}^{\mathrm{Min}} I_{jn} \qquad \forall j \qquad (5)$$

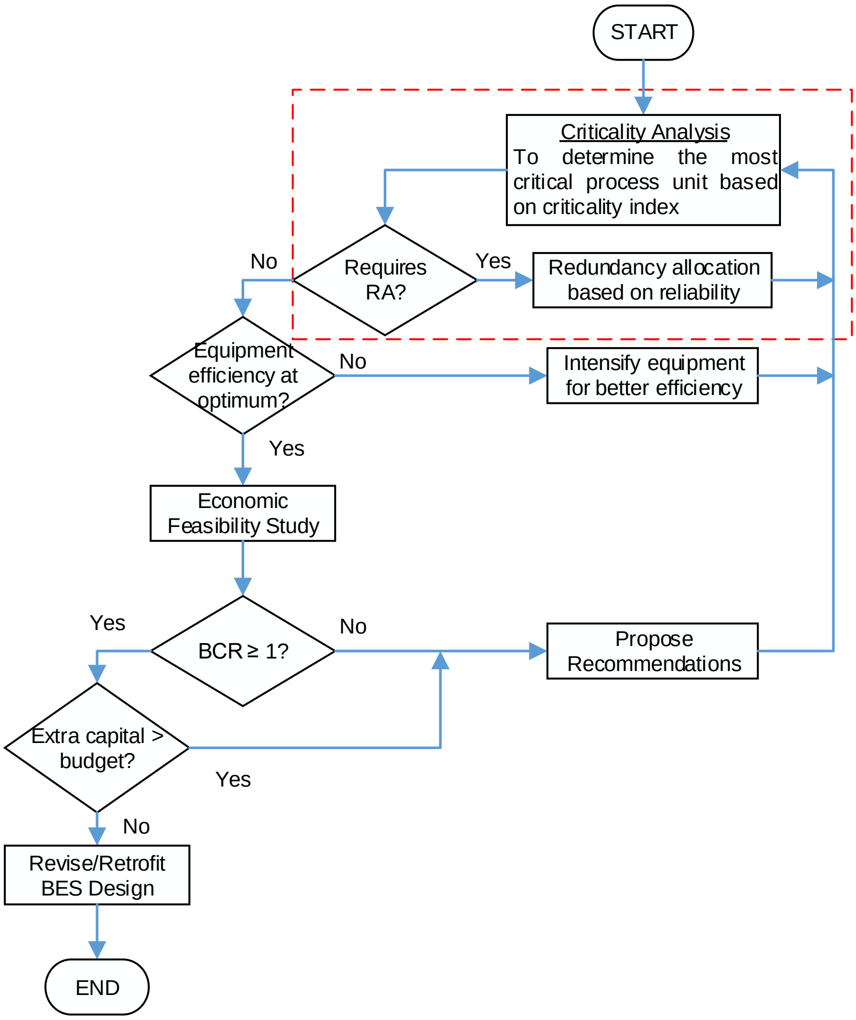

Figure 1: Framework for Addressing Criticality Issues via Redundancy Allocation or Process Intensification

where a_{wj} represents the matrix of input and output fractions to and from a certain process unit. x_j is the fraction of operating capacity for a process unit (where 1 represents a unit at 100 % operation, i.e., baseline capacity and 0 for a unit which is shut down). Meanwhile, z_{jn} and m_{jn} are positive integers which represent the number of operating and installed units with design capacity n selected in unit j respectively. Besides, P_{jn} is the reliability of design capacity n performing its function in unit j while R_{jn} ($m_{jn} \geq z_{jn}$) represents the reliability of design capacity n in unit j whereby at least z_{jn} out of m_{jn} number of units are operational. C is the binomial coefficient. R_j is overall reliability of unit j. I_{jn} is a binary integer variable which denotes the presence of a selected design capacity n in unit. $\mathrm{R}_{jn}^{\mathrm{Min}}$ is the minimum reliability level of design capacity n in unit j. M is an

arbitrary large number. On the other hand, process intensification refers to the use of innovative technologies in order to increase production efficiency. The approach of identifying critical units prior to RA is essential in cases where capital investment is too high to allocate redundancy for an entire system.
It is important to note that each step in Figure 1 is performed based only on one critical unit at a time. For instance, if a critical unit is addressed by allocating redundancy, it is important to ensure that the same unit does not appear to be a critical unit in the network before moving to the next step. Once the network design is clear of a criticality, it is up to the designer to assess for the next criteria which is process intensification, as shown in Figure 1. When the critical unit is addressed, subsequent step includes economic feasibility assessment. In the economic feasibility assessment, benefit-cost ratio (BCR) is used. BCR is the ratio of overall savings gained from proposed modifications in a system to the additional investment for modifications. If the BCR is greater than 1, it would mean that the benefits of the modifications outweigh the investment costs associated with the modifications. On the other hand, if the BCR is not greater than 1, new modifications must be proposed. In this respect, it is possible to consider an entirely new design all together. The following section of this paper presents a case study to illustrate the proposed framework in Figure 1. The case study focuses demonstrating the proposed framework on a palm based BES design.

4. Case Study

In this case study, criticality analysis is used to analyse and identify critical process units for the BES configuration shown in Figure 2. Process units in the BES include anaerobic digester (AD), membrane separators (MM), gas turbines (GT), heat recovery steam generators (HRSG), water tube boiler (WTB), dryer (DR), mechanical chiller (MCH), cooling tower (CT), high (HST) and mid pressure steam turbines (MST). Table 1 entails the results obtained from criticality analysis. Process units with a higher criticality index (i.e., units with higher percentage reduction in final output) are deemed more vital compared to other units in the BES. In this respect, it is found that AD, MCH, and CT yield the highest criticality index value. Such results suggest that if any of this process unit do not run at its baseline capacity, it will greatly affect its main product output when compared to the consequence of other equipment failure. For this particular BES configuration, it can be seen that most critical process unit (i.e., AD unit) is highly-connected to other equipment. To mitigate the consequence of such failure, the AD unit would require equipment RA. On the other hand, RA is not considered for MCH and CT units as further investigation into internal components (e.g., pumps, compressors, valves, evaporator, condenser, etc.) is required.

Table 1: Results from Criticality Analysis

Scenario	Disrupted unit	Baseline capacity	Product stream	Baseline net output	Disrupted net output	Fractional change	Criticality index	Rank
1	AD	319 kg/h	Biogas	0 kg/h	-3.2 kg/h	0.010	1.00	1
2	MM	316 kg/h	Biomethane	0 kg/h	-2.9 kg/h	0.009	0.92	2
3	GT	1,249 kW	Power	2,829.7 kW	2,818.2 kW	0.009	0.92	2
4	HRSG	1,580 kg/h	Flue Gas	34,137.7 kg/h	34,142.5 kg/h	-0.003	-0.30	4
5	WTB	39,268 kg/h	HPS	0 kg/h	80 kg/h	-0.002	-0.20	3
6	DR	11,951 kg/h	Dried Biomass	0 kg/h	198.8 kg/h	-0.017	-1.66	5
7	CT	56,218 kg/h	Cooling Water	14,999.1 kg/h	14,436.9 kg/h	0.010	1.00	1
8	MCH	1,000 kg/h	Chilled Water	1,000 kg/h	990 kg/h	0.010	1.00	1
9	HST	40,940 kg/h	Mid Pressure Steam	0 kg/h	681 kg/h	-0.017	-1.66	5
10	MST	40,940 kg/h	Low Pressure Steam	28,125 kg/h	28,806.1 kg/h	-0.017	-1.66	5

To allocating redundancy for AD, two nominal design capacity options are considered for this case study. Table 2 shows the respective reliabilities and CAPEX values for these two options. As shown, these two options include 100 % and 50 % nominal capacities respectively. Note that by choosing the 100 % option, spare 100 % units would be added to the already existing AD unit in the BES. On the other hand, if the 50 % option is chosen, the aforementioned existing 100 % AD unit must be replaced. Note also that the information on reliabilities can be obtained via typical/projected equipment failure rates for a given lifespan. However, the process of obtaining these reliabilities are beyond the scope of this work. Following this, equipment redundancy is allocated via the *k*-out-of-*m* modelling approach subject to minimising total CAPEX and a minimum reliability level of 95 %.
Table 3 shows the results obtained after equipment RA. As shown, an additional 100 % AD unit is chosen. This is because it is the most cost-effective option that meets the overall minimum reliability level of the configuration. Based on the results obtained, the BES configuration is revised to add an additional AD unit (Figure 2). Following this, criticality analysis is performed on the revised BES configuration to analyse if the

initial criticality of the AD unit has been addressed. Based from the recalculation, the final output of the AD is now 312.7 kg/h from a value of -3.2 kg/h. This suggests that the additional AD unit addressed the criticality via redundancy and the excess biogas can be sold or be used in other processes.

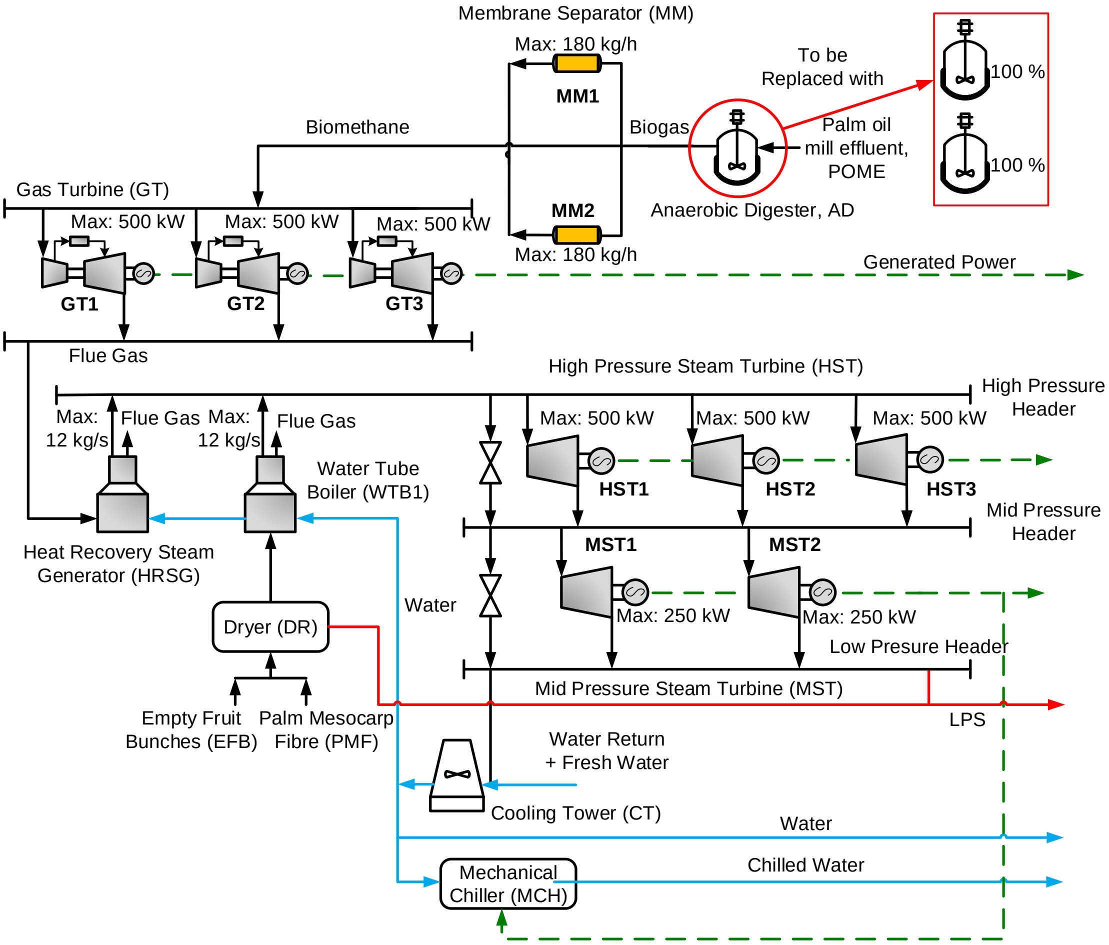

Figure 2: Revised BES Configuration after Redundancy Allocation

Table 2: Options for Redundancy Allocation (RA)

Options (Design Capacity)	100 % Capacity 55,500 kg/h	50 % Capacity 27,750 kg/h
Reliability (%)	92.0	90.0
CAPEX (USD)	660,450	330,225

Table 3: Results from Redundancy Allocation (RA)

	Results
Nominal Capacity Chosen	100 % Capacity
CAPEX (USD)	660,450
Additional AD Unit(s)	1
Total AD Unit(s)	2
Operating AD Unit(s)	1
Overall Reliability Level (%)	99.4

5. Conclusions

In this work, a novel integrated framework was developed to address criticality of process units in a biomass energy system via redundancy allocation. This two-stage approach enables design engineers potentially optimize economic resources at the same time increase the reliability of process units by identifying the critical component beforehand. The proposed approached is demonstrated using a BES and resulted in determining that the most critical component is the anaerobic digester (AD). The process bottleneck was eventually addressed using an additional AD unit with the same capacity (i.e., 100 % capacity). Future works will be directed toward extending the existing case study to consider process intensification activities as a method of addressing criticality within a BES.

Acknowledgments

The financial support from the Ministry of Higher Education, Malaysia through the LRGS Grant (LRGS/2013/UKM-UNMC/PT/05) is gratefully acknowledged.

References

Aguilar, O., Kim, J., Perry, S., Smith, R., 2008, Availability and reliability considerations in the design and optimization of flexible utility systems, Chemical Engineering Science, 63 (14), 3569-3584.

Andiappan V., Tan R.R., Aviso K.B., Ng D.K.S., 2015, Synthesis and optimisation of biomass-based tri-generation systems with reliability aspects, Energy, 89, 803-818.

Andiappan V,, Ng D,K,S., 2016, Synthesis of tri-generation systems: Technology selection, sizing and redundancy allocation based on operational strategy, Computers and Chemical Engineering, 91, 380-391.

Benjamin M.F.D., Tan R.R., Razon L.F., 2015a, A methodology for criticality analysis in integrated energy systems, Clean Technologies and Environmental Policy, 17, 935-946.

Benjamin M.F.D., Tan R.R., Razon L.F., 2015b, Probabilistic multi-disruption risk analysis in bioenergy parks via physical input-output modeling and analytic hierarchy process, Sustainable Production and Consumption, 1, 22-33.

Benjamin M.F.D., Cayamanda C.D., Belmonte B.A., Tan R.R., Razon L.F., 2016, A risk-based criticality analysis in bioenergy parks using P-graph method, Chemical Engineering Transactions 52, 1243-1248.

Coit, D., Liu, J., 2000, System reliability optimization with k-out-m subsystems, International Journal of Reliability, Quality and Safety Engineering, 7 (2), 129-142.

Frangapoulos, C., Dimopoulos, G., 2004, Effect of reliability considerations on the optimal synthesis, design and operation of a cogeneration system, Energy, 29 (3), 309-329.

Olsommer, B., Favrat, D., Spakovsky, M., 1999, An approach for the time-dependent thermoeconomic modeling and optimization of energy system synthesis, design and operation Part I: Reliability and Availability, International of Journal Applied Thermodynamics, 2 (4), 177-186.

Stankiewicz, A.I., Moulijn, J.A., 2000, Process intensification: Transforming chemical engineering, Chemical Engineering Progress, 96, 22-34.

Stoijkov, M., Hnatko, E., Kljajin, M., Hornung, K., 2011, CHP and CCHP Systems Today, International Journal of Electrical and Computer Engineering Systems, 2 (2), 75 – 79..

Voll, P., Klaffke, C., Hennen, M., Bardow, A., 2013, Automated superstructure-based synthesis and optimization of distributed energy supply systems, Energy, 50, 374-388.