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*Research Article*

# A Zero Waste Production Approach for the Large-Scale Crude Palm Oil Industry Using System Thinking and a System Dynamics Framework

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**Abstract:** Palm oil industry growth brings along its waste management obligations, at a very large scale. Its solid biomass residue, or waste, has a significant potential for energy resources. This study seeks to improve the knowledge of the dynamic behavior of a complex system from the perspective of a coupled waste and energy system. Based on a system dynamics (SD) modelling methodology framework with a multi-paradigm basis, it intends to employ a full-cycle, iterative approach and closed feedback-loop model structure, clarifying its difference from other studies that tend to have a linear behavior of an open-loop structure. The simulated model couples both the producer and consumer sub-models for introducing a non-linear system behavior using total crude palm oil (CPO) production data input and production ratio of different types of biomass residue materials, to enable an accelerated utilization rate of biomass residue derivative products. The results indicate three cases of growth rate (without and with coupling of sub-models, and with a multiplier coefficient to represent external intervention). This dynamic behavior arises by allowing the current practice of palm kernel shell (PKS) use as biomass fuel to be balanced with alternative biomass fuel such as empty fruit bunch (EFB), accelerating the utilization rate up to 100% of biomass residue (or being zero-waste) by simulated-month 125. This study serves as a valuable reference through the lens of a constructivist paradigm, by elaborating the applications of a full-cycle SD framework on a waste-to-energy system model, based on system thinking (ST), for getting insights into a complex system behavior.

**Keywords:** Biomass-residue; Complex-system; Palm-oil; System-dynamics; Zero-waste

## 1. Introduction

### 1.1 Motivation

Crude palm-oil (CPO) producer countries such as Indonesia and Malaysia, provide over three-quarters of global demand (Saeyang & Nissapa, 2021). The palm oil agroindustry often presents both sides of human impacts, economic prosperity, and environmental degradation. On the other hand, the global initiative on phasing down fossil-based solid fuel brings the opportunity for mainstreaming biomass residue use for industry fuel demand (Merzic et al., 2022). The circular economy (CE) concept identifies a ‘buyers-market’ situation as one of the barriers to shifting public perception from a linear economy (Jonsdottir et al., 2025). However, in many local situations, the excess availability of biomass residue is rarely viewed from the buyer’s market perspective. Hence, the consumer’s demand-pull perspective of the system, with its logistics works, may provide an alternative to those common analyses that often focus on technological solutions (Nemet, 2009).

The national production of crude palm oil (CPO) in Indonesia by 2023 was 47.1 million tons/year (BPS, 2024), with an annual growth rate that varies between 1% and over 3%, while over a decade ago, such growth could have been much higher than 3% (Sulaiman et al., 2024). Hence, by 2025, the national CPO production was about 50 million tons/year, generating solid

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biomass residue with an estimated 87 million tons/year. Typical solid biomass residue types are palm kernel shell (PKS), palm mesocarp fiber (PMF) and empty fruit bunch (EFB), often expressed as an output/input ratio in the palm oil industry. With the primary input of fresh fruit bunch (FFB) palm oil, an output/input ratio of 0.24 CPO/FFB; 0.064 PKS/FFB; 0.144 PMF/FFB and 0.21 The EFB/FFB ratio is typically expected (Syamsiro et al., 2019).

Among the types of solid biomass residue generated from a CPO industry (palm oil mills, or POM), PKS and PMF are used as boiler fuel for internal thermal processes (POM's own use), while some excess PKS and PMF are sold to external users. However, the EFB utilization rate for biomass fuel is considerably low (Samsu, 2022), citing the risks of boiler failure from EFB combustion fouling issues on the metal surface (Arifin et al., 2021). Estimated 89% of PKS and 92% of PMF generated from typical POM operations are used for the internal purpose of captive boiler fuel (Mustangin & Harnowo, 2020).

Considering the large difference between the utilization rate (Ut_rt) of EFB, which is much lower than that of PKS or PMF, there is a need to improve the consumer adoption of EFB derivative products through a reprocessing stage, for example, into torrefied-EFB biopellet fuel materials (Arifin et al., 2021). However, the recent urgency for accelerating the Ut_rt growth rate (while it should not wait for another decade) has raised the need to reframe such a complex waste and energy problem into a system perspective (Kemp-Benedict et al., 2012). Therefore, improving knowledge on such a complex system problem through system dynamics (SD) methodology framework is useful for identifying leverage points for system intervention.

This study aims to gain a systemic understanding of the waste and energy (complex) system for increasing the utilization rate of biomass residue (or waste) of the palm oil industry. This approach is unlike other SD models that may become over-complicated (or become less obvious for policymakers to understand).

This study addresses the research question on how to structure an SD model for integrating both sides of the producer and consumers to accelerate Ut_rt growth of biomass residue derivative products. This study introduces an overall feedback loop structure with coupling between sub-models to introduce both reinforcing and balancing loops to drive an emergent behavior in the system, as the dynamic hypothesis (detailed in the later section). This study hypothesizes that by improving the system behavior for accelerating biomass residue reprocessing into derivative products and coupling with the initiative for supporting industry consumers to adopt the product by improving its availability, the relationships within the waste-to-energy system is reshaped towards the zero-waste objective.

This study embarks on the journey to increase the Ut_rt value of biomass residue materials at the national level (taking Indonesia as a case study on a dominant palm oil producer country, for example). In a model simulation, the Ut_rt value may increase slowly every month through reprocessing into a derivative product to be consumed in the local market toward a target value of 100% Ut_rt (representing a zero-waste approach of managing the palm oil biomass residue). By taking useful insights from the SD simulation results, this study may contribute to providing inputs for designing strategic intervention options to influence the system (and decision-makers) for better managing the complex system. Furthermore, this study intends to provide a modular tool for enabling future development.

Previous studies on relevant subjects had several limitations, such as the lack of a feedback loop when using feed-forward data (non-loop behavior, with a more linear tendency). In other cases, a feedback loop may exist but is limited to a small loop covering just a few variables (while not considering several other variables outside such as small loop). Note that (Silalahi et al., 2020) study put a larger feedback loop in the model structure; however, its behavior was considered to be not very flexible, as it focused on specific rules for export tax (or levy) with a limited impact on specific types of palm oil producers (instead of covering more general industry players in the market). Another study (Arrumaisho & Sunitiyoso, 2019) on biodiesel production capacity investment put a larger feedback loop as well, but it was intended for existing product type in a well-established industry (instead of driving a new alternative product capacity, such as reprocessed biomass residue on a less-developed system environment).

**Table 1** Matrix for research position mapping, identifying gaps for scientific contribution

| No | Subject of study (or specific issues) | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Palm oil waste utilization (near zero-waste) | y | y | n | n | n | n | y | y | y | y | y |
| 2 | Waste-to-energy, or biomass-to-energy | y | y | n | n | y | n | n | y | y | y | y |
| 3 | System dynamics, SD (causal analysis) | y | y | y | y | y | y | y | n | y | n | y |
| 4 | Feedback loops (direct closed-loop causality) | n | y | n | n | n | y | n | n | n | n | y |
| 5 | Optimization (production volume) | n | y | n | n | y | y | y | n | n | n | n |
| 6 | Logistics (transport, supply-chain) | y | n | n | n | n | n | n | y | y | n | y |
| 7 | Product users, market (demand-supply) | y | y | y | y | y | y | y | y | n | n | y |
| 8 | Circular economy (bio-based) | n | n | n | n | n | n | n | y | y | y | y |
| 9 | Environmental analysis (impacts, climate) | y | n | n | n | n | n | n | n | y | y | n |
| 10 | Policy (socio-economic impacts) | n | y | n | y | y | y | y | n | y | y | y |
| 11 | Economic analysis (production) | y | y | n | y | y | y | y | y | n | n | n |

Note: y (yes); n (no); on each column that indicates references from previous-study as follows **A** (Abbasi et al., 2023) / **B** (Arrumaisho & Sunitiyoso, 2019) / **C** (Astria et al., 2021) / **D** (Muzayanah et al., 2018) / **E** (Newes et al., 2012) / **F** (Silalahi et al., 2020) / **G** (Wijaya et al., 2017) / **H** (Yeng et al., 2024) / **I** (Zahraee et al., 2019) / **J** (Zamri et al., 2022) / **K** (*this study*)

The research gaps on the system behaviour from system dynamics (SD) feedback-loop (direct causality) and logistics impacts on biomass waste products are identified from the mapping matrix in Table 1. Furthermore, another gap on the circular economy analysis with SD methodology is indicated. These opportunities for research work form the basis of this study.

One of the novelties is the utilization of an SD methodology framework with a closed feedback loop (direct causality), which drives a nonlinear behavior emerging from a series of stock-and-flow variables and delay parameters in a closed loop. Other research works that do not use such direct causality give the system behavior with an open-loop tendency, lacking a large feedback loop signal (so that system behavior tends to be predictably linear). By combining the subjects (research topics) from the right-hand column (**K**) in Table 1, this study attempts to close the scientific research gaps by building an applicable model for increasing the biomass waste utilization rate, Ut_rt, with a closed feedback loop using direct causality from logistics growth to the production capacity growth of biomass products.

This study does not intend to investigate production technology options for increasing biomass reprocessing activities. A novel approach on the modeling strategy applies a pull-production system as follows:

- Needs to consider specific consumer preferences for certain product types (on the 'buyer's market', as raw material volume exceeds market demand).
- The derivative product (reprocessed biomass residue) is assumed to be ready to start a growth stage, as the current volume remains low and will increase in the future.

Such production growth is expected to be accelerated (for not being a business as usual, BAU scenario), so that a higher consumption rate must be promoted.

This novel approach implements a pull-production system to close the loop in an SD model. By reconnecting product delivery to the market, the model structure provides feedback information from the logistics works to the producers of reprocessed biomass. Hence, the simulation results of this model serve as an enabling condition for relevant policy intervention by improving knowledge and insights on the dynamic behavior of the system over time (BOT).

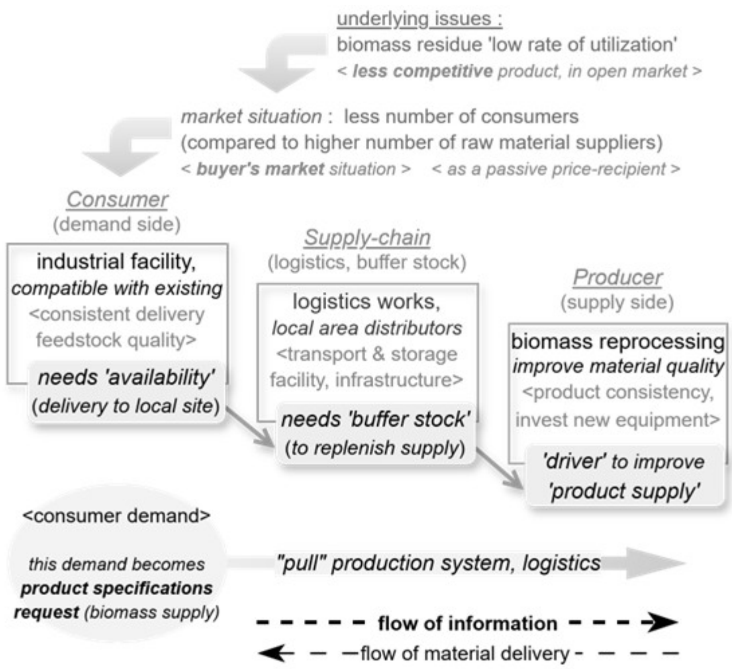



**Figure 1** Modeling strategy for a pull-production system

Both pull and push (production system, for example, product A) are applied in an SD model. The model structure enables leverage points for relevant interventions A1 or A2, such as the following:

- may improve logistics infrastructure, invest more in logistics assets for local distribution, and
- May increase the biomass reprocessing capacity, i.e., product-A (supply side management).

### 1.2 Assignment to biomass residue (or waste)

The term (biomass residue) (Jones, 1978) refers to solid by-products that may have some positive value, or in other words, represent no disposal cost (in terms of no net costs). Excess biomass (EFB, PMF, and PKS) materials are returned to the land in many POM sites, either at a local disposal site (adjacent to the POM site) or delivered back to the plantation area. Even when such excess biomass was partly used for local / captive boiler fuel, the resulting bottom-ash biomass materials were typically used by the local farmer's plantation area. Hence, palm-oil biomass is not regarded as waste, but rather as a biomass 'residue'.

The boundary of the global economy, within the earth system boundary, and options for the socio-economic cycling for the 'spaceship earth' were adopted from (Haas et al., 2020) and depicted in Figure 2.

For this study, the parameter 'rate of utilization' is related to the parameter rate-<sm>INPUT (or the ratio of <sm>/<pm>). For clarification on the boundary of this study, the simplified figure 3 indicates those material flows (dash-lines for product-derivative from reprocessed-residue materials, including flow of residue materials from palm oil mills).

## 2. Methods

### 2.1 Approach to the SD modeling study

Waste management is a wicked problem in environmental protection and management (Brett, 2024), particularly when multiple problems are coupled with (fossil) energy transition issues. In this study, the nature of the problem of increasing the utilization rate for biomass residue (or waste utilization) is also a wicked problem. This means that the observer person doing the research is inherently part of the system, taking an interpretivist position (instead as an external observer, looking from the outside of the system, as commonly found in the above positivism paradigm). Such an SD framework for modeling complex problems requires a multi-paradigm approach (Pruyt, 2006). Hence, an interpretivist view on the problem would apply as an alternative paradigm for this study.

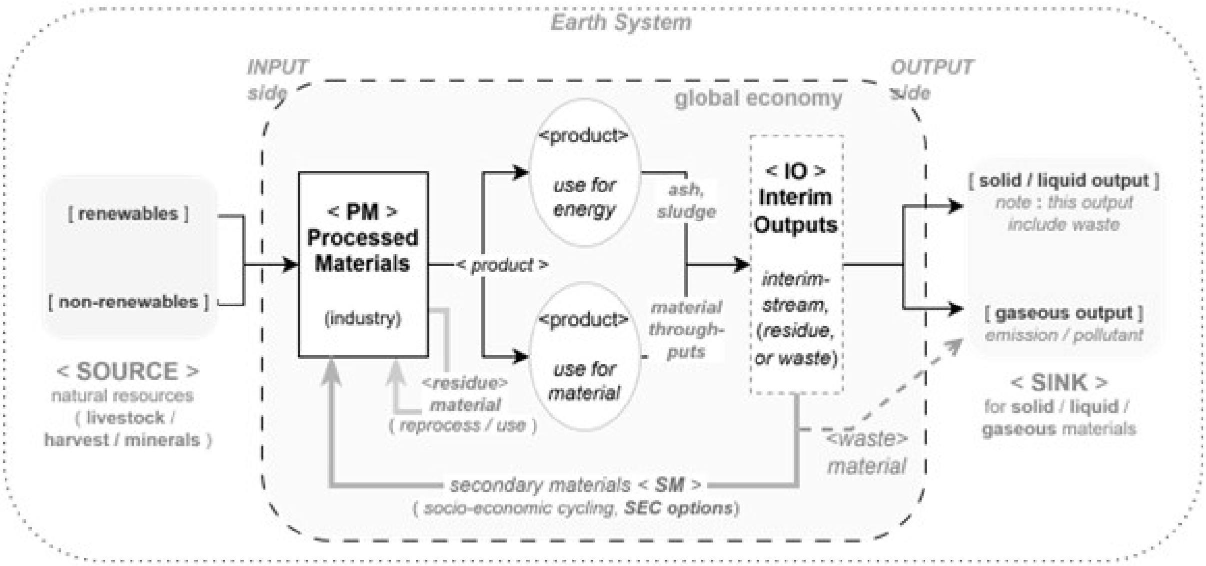



**Figure 2** Circularity material flow, adapted from Haas (2020)

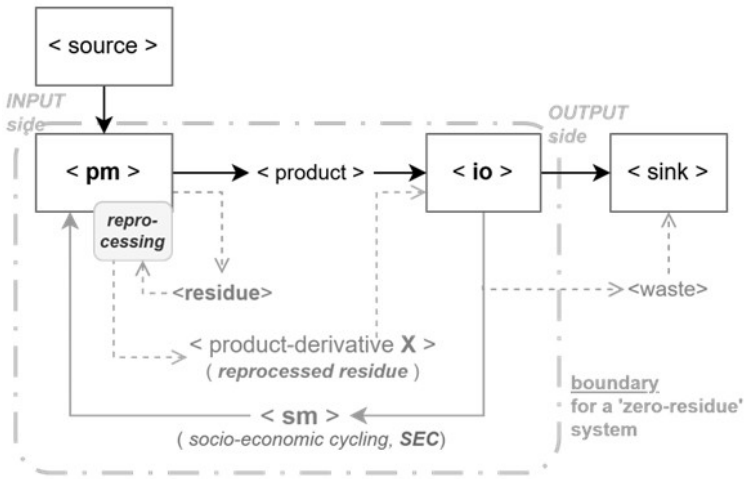



**Figure 3** Boundary for the zero-residue system (zero-waste objective)

The mental model used in this study is described as follows. The upstream CPO industry typically generates a large amount of excess material (residue) byproducts. On the other hand, the downstream industry often needs to develop a capital-intensive processing facility that creates the existing industry's path dependency (Pd), or a 'lock-in' situation, that puts a subjective limitation on the use of existing material type.

In a complex system, different components often influence each other. This creates another layer of a complex feedback loop with balancing- or reinforcing-loop behavior. Applying an interpretivist paradigm for the SD modeling framework provides useful insights for this study to structure an SD model, for example, by considering the buyer-market situation that involves biomass fuel consumers' behavior (or willingness to adopt a biomass-residue-derivative fuel product).

Based on a system thinking (ST) methodology and an SD framework, this study aims to provide insights for decision-makers (and policymakers) as a valuable input to develop system intervention and improve system behavior toward the intended zero-waste strategy. Following one of the properties of ST on the required ability to reduce complexity, the simulated model conceptually represents a basic (simplified) feedback loop between production and delivery logistics (Arnold & Wade, 2015). This reduced-complexity model serves as a tool for clear communication of the results. Hence, the extent of complexity needs to be maintained as manageable for the intended beneficiaries of this study (decision-makers and policymakers), considering the individual's cognitive perception and subjective knowledge.

Overall, this study applies a three-phase strategy, as illustrated in Figure 4.

- <phase-1> Identifying the context (socio-economics) and reflecting on the epistemological reference in this study.
- <phase-2> Studying a system's dynamic behavior, beginning with a qualitative model structure, and analyzing quantitative model simulation results.
- <phase-3> Expanding the causal-reasoning narrative to indicate a few insights and translating outputs into outcomes with possible impacts on improving the real case situation.

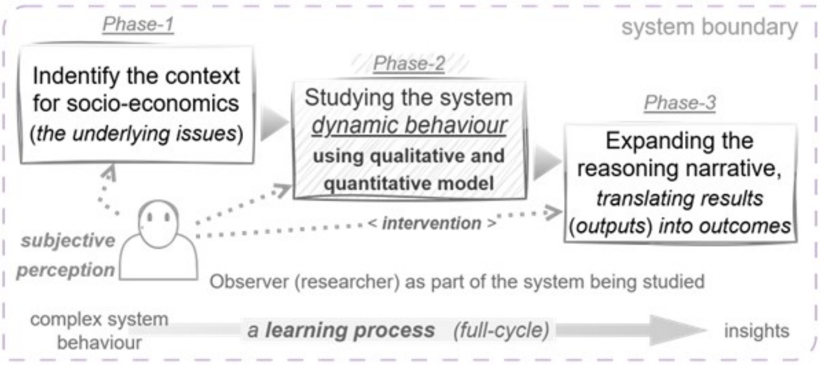



**Figure 4** System and observer used to address complex problems

## 2.2 Research methodology

The system dynamics, SD methodology is used to apply both qualitative and quantitative modeling by adopting some parts of the seven management and planning tools in the total quality management domain (Anjard, 1995; Brassard, 1989). A full-cycle SD methodology framework applies both quantitative and qualitative reasoning to support a second-order intervention (SOI) for improving Ut_rt (of biomass residue, in a real-world situation). Instead of limiting the study to developing an SD model and analyzing the simulation data results, this study uses both inductive thinking and deductive analysis. Hence, the overall SD approach is described in a five-step methodology, as shown in Figure 5, adapted from (Pruyt, 2006).

## 2.3 Dynamic Hypothesis and Full-Cycle SD Methodology Framework

The dynamic hypothesis, presented in a causal loop diagram (CLD), is described in figure 6 below, refers to figure 6(a), which indicates the complex relationship between:

- stock and flow of biomass residue reprocessing component (representing the waste system or supply-push production system), and
- The stock and flow of the derivative-product logistics component (representing the energy system or the demand-pull production system).

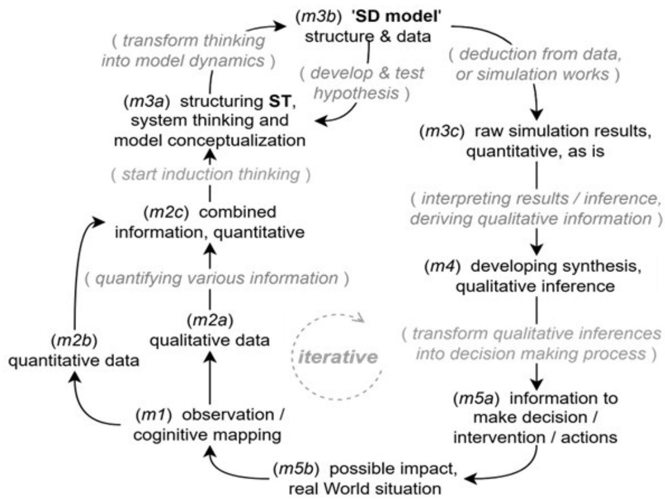


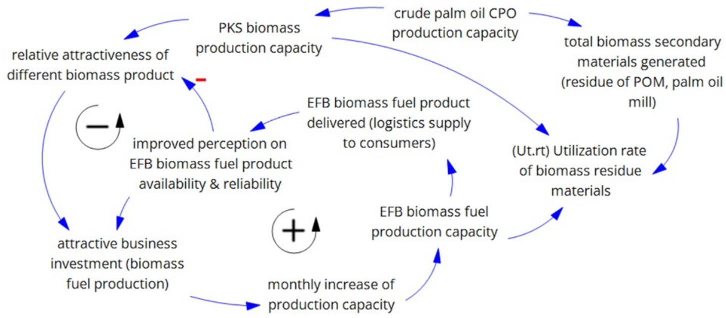

**Figure 5** Overall SD methodology framework cycle (m1–m5), adapted from Pruyt (2006)

The dynamic hypothesis is based on the "complex system behavior of a coupled problem (waste and energy)." This represents a Path Dependency (Pd) to an existing production infrastructure. A system-thinking-based strategy for intervention options may enable behavior changes in several subsystems intended to increase the utilization rate of biomass residue generated by the palm oil industry". Such dynamic hypothesis is intended to clarify each role of subsystems to inform decision-makers (or policymakers) to design relevant interventions at the system infrastructure level.

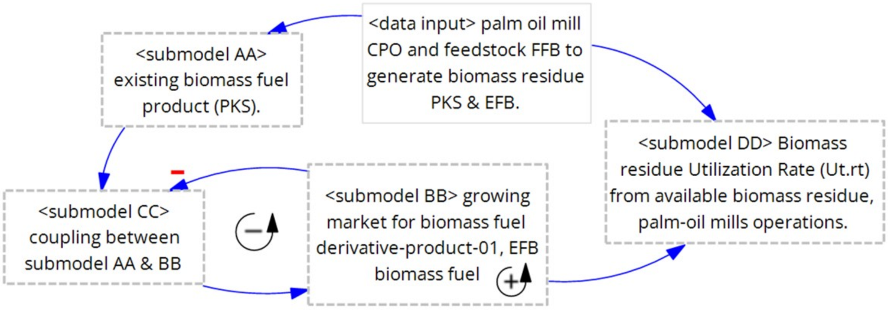
A specific SD model is structured with several model parameters, such as stock-and-flow variables, converter variables, and input values, based on the SD methodology. The independent variables are the amount of CPO delivered to the market at the national level, the CPO product growth rate, the initial values of the stock of PKS and EFB biomass residue, the typical delay of one year, the policy intervention constant, and the FFB, CPO, PKS, and EFB output/input ratios. On the other hand, the dependent variables are, for example, a production capacity growth on EFB residue reprocessing, an increasing supply of EFB derivative products into logistics for biomass fuel consumers, with the improved perception on EFB biomass fuel, and feedback into a variable for the product's relative attractiveness, and variable attractive-investment of biomass production, and finally the value of utilization rate (Ut_rt).

Figure 6(a) describes the causal relationship between individual parameters (and between sub-models as in Figure 6(b)) in a CLD format, indicating relevant feedback loops. The reinforcing feedback (with '+' sign) is structured within the sub-model for a growing market for the reprocessing of biomass derivative products (EFB biomass residue). Another balancing feedback loop (with '−' sign) is also structured between the sub-models of the growing market for biomass derivative products and the coupling sub-model. Both feedback loops introduce dynamic (non-linear) behaviors into the complex systems of biomass residue and energy, with the coupling of sub-models covering both the production and consumption sides of an integrated waste-to-energy system.

The SD model is checked against the behavior of a commodity market development in a typical real-world situation upon simulation. The coupling between two different products with each characteristic (PKS as a dominant product, while EFB represents a new alternative product type) was indicated by the S-curve behavior of a new product development (e.g., EFB biomass residue derivative product. The model validation approach is described in the following section.




(a)




(b)

**Figure 6** Dynamic hypothesis (CLD) and network of sub-models, for coupling local feedback loops *a) Dynamic Hypothesis b) Network of submodel. Note: The coupling between sub-models BB / CC is a balancing loop, and another local loop is a reinforcing loop within the internal sub-model BB (for accelerating Ut_rt growth).*

## 3. Results and Discussion

### 3.1 Qualitative results of the feedback loop structure

To address the 'what' question on the system structure, the proposed module contains a coupled 'biomass-residue reprocessing and logistics' sub-model with three stock parameters (sometimes termed 'level' variable) in an internal feedback loop. The stock parameter represents the supply-side push (residue reprocessing, e.g., biomass fuel pellet). Another stock variable represents the demand-side pull (logistics work to support product delivery to consumers, hence improving product availability at the local level).

Furthermore, to address the 'why' question, a causal interelationship makes it inseparable between the biomass-residue reprocessing side and the logistics side within a sub-model of one product type. When perceived as a separate item, the biomass-residue reprocessing part and the logistics work part may seem to grow independently of each other. However, as consumers perceive both as an integrated system (for example, when placing a delivery order of a certain quantity of biomass fuel), both parts simultaneously develop within a two-way causal relationship. To meet the expectations of industrial consumers regarding large-scale product delivery and consistent reliability, a policy intervention designed to accelerate the biomass-residue utilization rate needs to understand both parts as a single system.

To address the 'how' question, the dynamic behavior of the system (following CLD on dynamic hypothesis with the first component <biomass production> and the second component <logistics>) is as follows:

- The PKS biomass fuel product continues to dominate due to existing consumer lock-in with sufficient product quality, this represents a 'path-dependancy' logistics behavior.
- External system influence such as different policy set-up (or explicitly setting more behavior constraints, e.g. to limit consumer preference on PKS product or to promote

other alternative product types) enables internal system changes, which accumulate over time and overcoming the path-dependency (Pd) behaviour

When the system operates at the baseline scenario (or reference mode), the typical baseline growth rate of biomass reprocessing and its utilization rate, Ut_rt, is relatively slow, possibly in the order of $< 0.5$ % per year. A couple of leverage points could be used within the biomass-reprocessing sub-model to accelerate Ut_rt increase in the intervention scenario.

To enable an accelerated growth of the biomass-residue utilization rate, the policy intervention may focus on intervention entry points (IEP). The first one (IEP.1), or leverage point for increasing biomass reprocessing, is achieved by using the first feedback loop to increase the value of 'multiplier coefficient' for the 'inlet-flow parameter: add-biomass-fuel-product. The second one (IEP.2) is achieved by using the second feedback loop to further enhance the capacity growth of biomass reprocessing (through another leverage-logistics multiplier factor).

Note that IEP.1 and IEP.2 are linked to the same 'inlet-flow parameter': add-biomass-fuel-product (as the same mathematical multiplication operator). However, even though both leverage / entry-point parameters are numerically similar, the real-world implications tend to be quite different or unique in their causality, purpose, and strategy.

First, IEP.1 is implemented through a supply-push situation (where production facilities are intentionally expanded, for example, through sectoral government policy). This IEP.1 option serves as a policy driver for requesting the CPO producer management entities (as the 'owner' of biomass residue) to invest more in higher capacity biomass reprocessing units.

Meanwhile, for implementing IEP.2, the additional investment may take the form of a market demand-pull, where more biomass product consumers are served in a better logistics works. This pull eventually comes from satisfied consumers (by the reliability of product delivery) that meet their specific needs, for example, in terms of purchase time and volume availability.

### 3.2 Quantitative results of the coupled-model simulation

Following the interpretivist position of the SD modeling work described in the above methodology, the SD modeling results intend to drive a policy change, as a higher-level leverage point (Meadows, 1999). By emphasizing the qualitative behavior of a complex system (instead of focusing on an absolute numerical value, which aims to have control on a lower-level leverage point), this study examines a certain trend on the graphical results, which represents a desired system behavior.

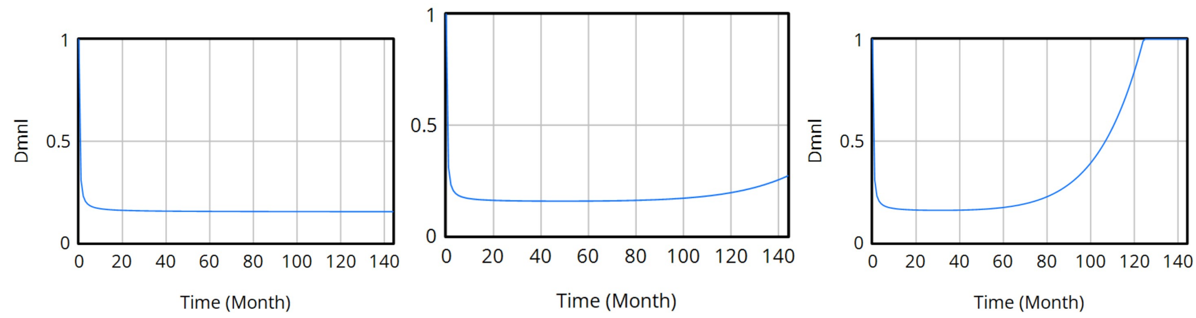
The quantitative results presented in this section are intended to support the policy intervention, where the simulated value for parameter Ut_rt is as follows:

- When the biomass reprocessing growth rate does not consider the leverage-logistics, the growth rate of the biomass residue Ut_rt seems to have a very low value, as illustrated in Figure 7(a).
  - Graph shows a nearly flat curve (growth $\sim 0$),
  - the very low growth value (being slightly higher than zero value) comes from the baseline growth rate, $< 5\%$ per year, as described in the qualitative results section.
- The growth rate of biomass residue Ut_rt may increase at a relatively low rate when the system considers the leverage-logistics / feedback loop. Figures 7(a) and 7(b) show a comparison.
  - biomass-reprocessing sub-model is expanded into the overall model simulation, as described in <step-3> in the previous section,
  - With such a low growth rate, the zero-waste objective is not fulfilled (even after 12 years, or the simulated month 144).

  - this case represents the absence of an additional value for intervention 'multiplier coefficient' for the 'inlet-flow parameter': add-biomass-fuel-product (multiplier value is 1), as illustrated in Figure 7(b).

- Further increasing the Ut_rt growth rate by raising the multiplier-coefficient value = 1.5 (as an intervention or leverage point) is illustrated in Figure 7(c), in comparison with the previous simulation with multiplier value = 1 in Figure 7(b).

  - With this increased growth rate, the zero-waste objective is fulfilled (i.e., after 10 years or the simulated month 125).




(a) (b) (c)

**Figure 7** Simulation results for the utilization rate (Ut_rt) value for the 144-month simulation period *(a) Simulated Ut_rt value: no logistics feedback, sub-model<step-1> (b) Simulated Ut_rt value: on logistics feedback, sub-model<step-2>, but no intervention (multiplier = 1) (c) Simulated Ut_rt value: on logistics feedback, sub-model<step-3>, and with intervention (multiplier = 1.5)*

Note that the numerical results presented here are indicative values. For example, the multiplier-coefficient value of 1.5 is taken as a 50% increase of its baseline value (or a sensitivity check). This agrees with the (higher-level) leverage point aim, as the simulation result is useful in identifying a higher-order intervention strategy, such as

- Locating the intervention point that indicates the intended impacts to improve system behavior,

- checking the relationship between system parameters and sub-models, being relevant to the intervention points (and further options to extend the knowledge of producer-consumers sub-systems coupling, or emergent behavior), and

- communicating the model structure, with the growth rate parameters as a result of the causal relationship of sub-models (or certain quantitative impacts of reinforcing / balancing feedback loops).

### 3.3 SD simulation results and validity check

This section describes a conceptual basis for validation works. This validation approach is intended to be consistent with the purpose of the SD framework. It considers adopting the interpretivist paradigm (similar to second-order cybernetics, with focus on 'observing system' and 'self-reference') (Schwaninger, 2019) into the learning-intervention theory (De Wijse-van Heeswijk et al., 2025). This study is intended to provide a second-order intervention (SOI). This approach is taken, instead of doing a first-order intervention (FOI) that focuses on regulation and direct-information. Both FOI and SOI are described in Table 2.

When a full-cycle SD methodology is applied (based on system thinking), the intervention options is not a first-order intervention, FOI. An FOI represents a 'direct intervention' by providing technical instruction (e.g., directly changing the input value during operations). However, such FOI is not intended to be the focus of the SD framework. In some other cases, when some other SD model structure uses a more 'linear SD model' characteristics (having mostly 'feed-forward' flow of information, instead of 'feed-back' loops), such FOI could be proposed as an insight within a research domain of 'engineering-process System Dynamics' methodology (**ep.SD**).

**Table 2** Indicators for intervention, first- and second-order

| Subject | First-Order Intervention, FOI | Second-Order Intervention, SOI |
|---|---|---|
| Actor | Operational entities | Higher-level entities (e.g. regulators, or third-party team) |
| Action | Change input value | Develop regulations, or policy for entities doing technical work |
| Purpose | Applying norms or operating procedures (SOP), to clarify decision on technical activity | Improving norms (adapting the system's structure), to serve as enabling conditions |
| Impact | Content of the works is directly changed (e.g. by corrective action) | The system's overall process is changed (when needed), to influence behaviour changes, e.g. by persuasive actions, or by setting up additional constraints |
| Circular economy stage | FOI on a first-generation circular economy <1G.CE> direct-action, implement environmental works, for reducing direct-impacts (earth ecosystem, physics/bio) | SOI on a *second-generation circular economy <2G.CE>* indirect-action, encouraging 'economic policy' for enabling conditions (industry ecosystem, business) |
| Research Domain of SD method | 'engineering-process System Dynamics' methodology (**ep.SD**) | 'system thinking for a System Dynamics' methodology (**st.SD**) |

On the other hand, the SOI intends to change the overall process, instead of directly changing variables at the local level (De Wijse-van Heeswijk et al., 2025). SOI could be implemented through a learning process (supported by ST and SD modeling, for example) to understand the system's dynamic behavior and adapt the operational rules or technical policy. The SOI intends to 'indirectly' change the operations with policy works to influence the overall flow of the process (and the technical/ social behavior of relevant entities). SOI is active within the research domain of 'system thinking for a system dynamics' methodology (**st.SD**).

By understanding the insights from simulation results based on SD modeling framework, relevant policymakers may implement SOI on a complex system. Such SOI may serve as a moderation (setting up behavior constraints, indirect purpose) for the FOI (direct corrective actions), for example, by re-adjusting the regulations / management policy to enhance organizational performance or competence of relevant entity (either in the technical operations or in the management team) (Schwaninger & Ríos, 2008).

As the overall paradigm is based on interpretivism (starting from the development of the model structure, to complete a full-cycle of the SD framework / adopt modeling insights for intervention, refers to Figure 5 above), the model validation approach (Schwaninger & Grösser, 2016; Sterman, 2000) is as follows:

- A goal-oriented activity, where the goal or purpose of developing an SD model structure is as follows:
  - for being able to indicate the rate of utilization (of palm oil mill's residue, or waste materials, toward implementing a zero-waste production strategy), and

when possible, approaching the target of 100% utilization rate,

- To provide tools (decision support) for managing the complex problem of energy and waste (as a coupled system),

- The validated SD model is perceived as being useful (instead of being absolutely right) for the purpose assigned to that model.
  - hence fulfilling the validation purpose
- It should also be noted that the validity of the SD model is accepted as a relative concept.
  - The validity of the model is not an absolute truth (in quantitative terms).

The validation of the structure and behavior of the SD model (on the direct structure test and the structure-oriented behavior test) is described in Figure 8. To follow up in more detail, Table 3 summarizes the SD model validation.

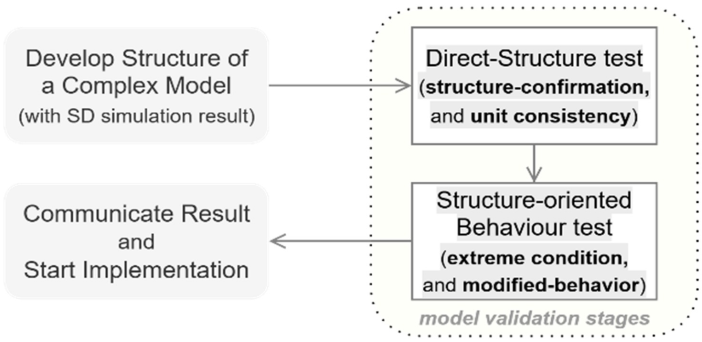



**Figure 8** Stages of the SD model validation

**Table 3** Model validation approach and results

| Validity by | Approach validity test |
|---|---|
| <v.1a> Structure-confirmation (direct structure tests) | Equations for (subsystem PKS & EFB biomass fuel) is compared with (PKS & EFB production, in real system) |
| <v.1b> Dimensional consistency (direct structure tests) | The unit of each variable's numerical value needs to be thoroughly re-checked, for maintaining consistency with all of their mathematical relationship |
| <v.2a> Extreme-condition (structure-oriented behaviour tests) | Test with input value (set as very high, or zero value) for the sub-system, then as logical consequence, overall system behaviour will change, accordingly |
| <v.2b> Modified-behavior prediction (structure-oriented behaviour tests) | Overall SD model should indicate behaviour-tendency similar to common pattern of real-system behaviour |

The results of the validated model structure <v.1a> <v.1b> indicates that

- Value of PKS production and consumption represents the actual value (i.e., CPO production at a national level is 50 million tons per year, with an output/input ratio of 0.24 CPO/FFB; 0.064 PKS/FFB; 0.144 PMF/FFB and 0.21 EFB/FFB), and
- rechecking the detailed model consistency for the units of each numerical value (following their causal relationship between variables) reconfirmed that the unit of all variables

and their mathematical relations remained consistent throughout the causal loops of the model.

The results of the extreme-condition test in the model behavior <v.2a> validate the following:

- in an extreme case where the PKS input variable is set to 0 (zero) value, the EFB consumption value indicates an accelerated increase to a very high value
  - in this case, the PKS supply is stopped (all consumers use EFB instead of PKS for biomass fuel) so that EFB consumption increases rapidly (not limited by product competition with PKS).
  - This is due to the reduction of complexities in the overall system (EFB product growth continues).

The results of the validated model behavior prediction (structure-oriented) <v.2b> indicates that

- when the variable of the product's relative attractiveness is set to 1 for the EFB biomass residue reprocessed-product growth rate (so that the intended coupling between PKS and EFB sub-model is abandoned), then the EFB reprocessing capacity growth cannot accelerate, hence its resulting value stagnates
  - if the subsystem for 'demand PKS product' operated under condition 'keep increasing consumption rate', this causing the 'EFB biomass fuel product amount value becomes stagnant or remains flat.'
  - this is due to the EFB product being not competitive in the market, while PKS being the winner in the market
- on the other hand, when the variable of EFB biomass residue reprocessed-product growth rate is set to reflect the product's relative attractiveness variable (so that the intended coupling between PKS and EFB sub-model is active), this drives an accelerated capacity growth for EFB reprocessed-product; hence, the resulting Ut_rt value continues to increase toward 100% utilization rate
  - if the subsystem for 'demand PKS product' operated under condition 'constant consumption rate', then 'EFB biomass fuel product amount, value increasing in S-shaped growth' would result, as in a typical new / alternative product development stage,
  - This is due to a change in system behavior: EFB becomes the winner in market competition.

### 3.4 Discussion

This study intends to identify relevant strategies for incorporating reprocessed biomass residue products into regional economic activities as a second-generation CE (or 2G.CE) (Mathies, 2025). Alternatively, a next-generation circular economy approach may be adopted (Henseling et al., 2021), for example through the EU second-communication (Kovacic et al., 2019). In line with the global transition agenda, 2G.CE emphasizes economic instruments and growth, driven by business entities and economic stakeholders (including consumers, policymakers, etc.).

Such a strategy involves second-order intervention (SOI) as part of policymakers' work to support the industry ecosystem in adopting practices on reprocessing biomass residue materials. These insights provide a basis for policymakers to develop system intervention options. A concise representation, with visualized system behavior, is useful to translate those insights into causal-reasoning narratives through system thinking works and a full-cycle system dynamics framework.

Simulation results indicate system behavior, such as a (long-term) path dependance (Pd). This is partly due to product availability for the nationwide consumer order (logistics issues). Possibly also due to the particular characteristics of the physical qualities of the biomass fuel product (EFB-based). To break the path dependency (Pd) on the prevalent PKS biomass fuel, relevant intervention in terms of policy and technical improvement is needed. The narrative can be structured as follows:

- The Pd behavior of consumers (and producers) regarding the biomass residue derivative-product needs to be shifted (or 'breaking the Pd').
    - The reinforcing feedback loop must be initiated,
    - By improving the quality of reprocessed products and reducing logistics bottlenecks (supporting a more efficient supply chain).
- The pull-production system (i.e., causal loop diagram) should consider
    - consumer preference on specific product types
    - in a 'buyers-market', the consumer behavior becomes a decisive factor

In this study, insights from the interpretivist paradigm (through second-order intervention, SOI, instead of FOI, that refers to the above section) are based on an indirect approach. Hence, the critical role of regulators (national / local government entities) in supporting economic growth for realizing a 2G.CE is provided as supplementary material or infographics. Such visualization of the underlying system structure indicates leverage points for system intervention. This also facilitates clear insights for decision-makers (e.g. regulators, business entities, etc.) to increase their influence on relevant system behavior and structure to shift the system behavior toward the intended objective of a 'zero-waste production strategy'.

The terms and language selected for developing policy interventions, further facilitated by an infographic for example, need to be simplified. Such as using technical terms when necessary, this can be focused on building knowledge on the system structure. The dynamic behavior is an emergent property of the system structure. Hence, by understanding relevant sub-models and their causal relationship between components, and also a direct coupling between sub-models, the required policy (developed as a second-order intervention) is more targeted to improving the overall system behavior over time (BOT). This system approach is preferred, instead of doing partial improvements to some parts of the whole biomass-residue production and usage system.

This study intends to implement a full-cycle SD methodology framework instead of a partial SD methodology that relies heavily on SD modeling-simulation and direct analysis of the results. Using an interpretivist paradigm, addressing problems in a complex system (using an SD framework) provides valuable insights for developing indirect, second-order intervention SOI options. As the observer / researcher is part of the complex problem, such SOI contributes to the initiative for managing the complex problem (instead of relying on a direct solution, or first order intervention FOI, as often happens in addressing other engineering problems).

## 4. Conclusions

This study has identified the dynamic behavior on a complex problem of waste and energy system domain, as a long-term strategy for increasing the utilization rate of biomass residue generated in a very large amount by the palm oil industry. In the base case (without parameter coupling between production and logistics parts), a low growth rate of biomass reprocessing capacity does not produce a noticeable increase in $Ut\_rt$ value throughout the full simulation period. In the second case, coupling those parameters indicates a small increase in $Ut\_rt$ (but remains at a relatively low level, being unable to meet the intended Ut_rt value of 100%). The third case represents a higher growth rate. As the biomass residue Ut_rt gradually approaches 100% (by the time of simulated-month 125), the strategy for zero-waste industrial process is slowly fulfilled. These results indicate a non-linear system-behavior response for an integrated SD model with larger-feedback loops, thus closing the research gaps on a complex system knowledge development, while applying an iterative SD framework methodology for managing complex problems. This study also contributes to addressing the wicked problem of waste management, coupled with the need to improve the sustainability of an energy system, that represents a complex system analysis.

## Conflict of Interest

The authors declare no conflicts of interest.

## Supplementary Materials

Program listing file, biomass residue Ut_rt (.pdf file, reformatted copy, converted from .mdl Vensim file).

Infographics: 'Translating Insights from System Dynamics Framework to System Intervention' (.pdf file).

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