TASK-BASED LCA FOR ENVIRONMENTAL IMPACT ASSESSMENT OF MULTIPLE HETEROGENOUS SYSTEMS

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Abstract

Life Cycle Impact Assessment (LCIA) is the framework for assessing the environmental impact of a product over its entire lifecycle. There have been numerous LCIA studies in the past conducted on stand-alone heavy-duty machines, but the usefulness of the methods in these studies is limited when the goal is to compare the environmental impact of two cotton stripper designs. Cotton strippers do not operate in isolation — they always operate in unison with supporting machinery such as tractors, or tractor-powered machinery, which means any meaningful comparison of cotton stripper designs must also account for the close coupling between cotton strippers and their supporting machinery. This paper proposes a new framework for comparing the environmental impact generated by two cotton harvesting systems. The proposed framework is task-based in the sense that a series of common tasks defined on a given field serve as a standard unit of work in a fair comparison of the two cotton harvesting systems. A simulation model is used in the proposed framework to simulate the movements and interactions of the machines on the field.

Keywords: Design for X (DfX), Sustainability, Ecodesign, Design practice

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1 INTRODUCTION

This paper proposes a framework for comparing the environmental impact of two cotton harvesting systems. The first system, denoted as System A, comprises a cotton stripper, a cotton module builder, and a tractor-pulled cart that transfers cotton from the cotton stripper to the module builder. The second system, denoted as System B, comprises a multi-function cotton stripper and a tractor. The cotton stripper in System B not only strips cotton, but also packages the cotton into modules, and releases completed modules out the back and onto the field. The modules are then picked up by a tractor which moves the modules to a corner of the field. Recent works of a similar nature have compared haymaking machines (Bortolini et al., 2014), and tractors with different engines (Mousazadeh et al., 2011). This paper differs from previous works in two ways.

First, the proposed framework expands the boundary of the analysis from a single machine to a system of machines. The main problem with focusing solely on a cotton stripper is that cotton strippers do not operate in isolation — they require supporting machinery, such as module builders, and tractors for moving the harvested cotton. In fact, the characteristics of the supporting machinery can have a great effect on the utilization, and hence environmental impact of the cotton stripper itself.

In a field study conducted by Faulkner et al. (2011) that compared the efficiency of cotton strippers and picker harvesters, it was observed that the time the harvester spent harvesting and idling was greatly dependent on the number of carts available. Conversely, the design of a cotton stripper can also greatly influence the behaviour and nature of its supporting machinery. Expanding the boundaries of the impact assessment to include interactions between the cotton stripper and its supporting machinery gives a more comprehensive picture of the environmental impact of different cotton stripper designs.

Second, the proposed framework compares the impact generated by the two systems from performing a series of common tasks on a given field. This is in contrast to previous works that conducted a separate Life Cycle Assessment (LCA) study on each machine. Given the long lifetime of these machines, and different usage scenarios that these machines can encounter throughout their life, it may be hard to obtain meaningful conclusions from a comparison of two separate LCA studies. That is why in the proposed framework, the two systems are compared on the impact generated from performing the same tasks on the same field. These common tasks provide a standard quantity of work that ensures an "apples-to-apples" comparison between the two systems.

In the proposed comparison framework, the movement and interactions between the cotton stripper and its supporting machinery are created using a simulation model. Simulation, and other analytical tools, such as cycle diagrams used by Buckmaster and Hilton (2005); and Brownell et al. (2012), or mathematical models (Hansen et al., 2007), have been applied in the past as an acceptable alternative to conducting time-consuming field trials while still offering a reliable level of accuracy.

The next section describes the proposed framework in greater detail, followed by a description of the simulation model, and the results of the comparison. Finally, the proposed framework was used to evaluate an impact reduction design improvement in System B.

2 FRAMEWORK

2.1 Task definitions and field properties

Each cotton harvesting system is assessed on the impact generated from completing 3 tasks on a rectangular field with its properties shown in Table 1. The cotton stripper starts at point S as shown in Figure 1, and moves in an alternating path until it reaches the end of the field. The solid arrows in Figure 1 represent a harvesting pass by the cotton stripper, while the dotted lines indicate a turn. The field chosen for the comparison is rectangular, with length of 805m, and breadth of 203m (or equivalently, 25 cotton stripper passes). The yield of the field is expressed in terms of ginned cotton per unit area, where ginned cotton refers to the cotton fibre that is extracted from the cotton plant.

Table 1. Field properties

Row spacing	1.01 m
Length	805 m
Width	203 m
Yield (ginned cotton)	0.109 kg / m2

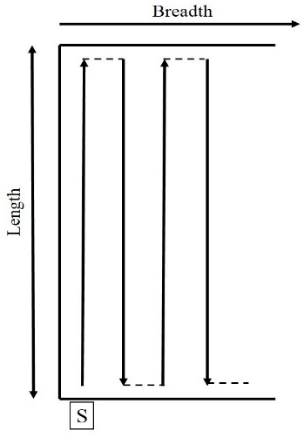

Figure 1. Field shape and cotton stripper path

The three tasks both systems must complete are:

1. Strip the cotton from the rectangular field.
2. Move the harvested cotton to starting point S.
3. Package the harvested cotton into modules.

The above tasks, and the field properties in Table 1 represent a typical cotton harvesting scenario that can be used to compare the two cotton stripping systems. The tasks can be seen as objectives that each system must carry out, although not necessarily in the order stated. From a simulation modelling perspective, the tasks are stopping conditions for terminating the collection of simulation data.

The task breakdowns for each system are shown in Figure 2. In System A, each component is responsible for carrying out a single task. The cotton stripper strips the cotton and stores the cotton in its storage basket. Once the basket is full, the cotton must be transferred to the tractor-pulled cotton cart, which then moves the cotton to the module builder located at point S. The module builder compacts the cotton into rectangular modules that are ready for transport to the cotton gin.

In system B, the 3 tasks are handled by 2 machines. System B's cotton stripper combines the functionality of System A's cotton stripper and module builder. Not only is it able to strip cotton (task 1), but it can also package the cotton into a module (task 3). The completed modules are dropped onto the field, and a tractor is used to move the modules to point S. Another interesting design feature of System B's cotton stripper is its ability to carry a completed module on its back. This carrying ability reduces fuel consumed by the tractor since it has to travel a smaller distance to move the modules to point S.

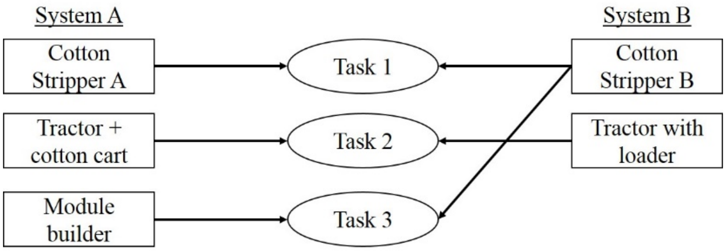

Figure 2. Task allocations in both systems

2.2 Impact calculation

A simulation is carried out for each system to obtain the durations of each machine in completing its assigned tasks. The inputs to the simulation are averages, so the output durations are deterministic, but the framework could easily be extended to the stochastic case. The durations generated by the simulation are then used to calculate the environmental impact generated by the two systems. The environmental impact generated by a system is further broken down into three categories — equipment impact, usage impact and packaging impact.

Environmental impact is expressed in terms of Life Cycle Impact Assessment metrics such as Global Warming Potential (GWP) (Solomon et al., 2007), and Eco-Indicator 99 (EI-99) (PRé Consultants, 2013). These metrics provide a way of quantifying the environmental impact of a process. Every impact metric is focused on different aspects of environmental degradation. For example, the GWP score only assesses the warming potential of greenhouse gases released by a process, whereas Eco-Indicator 99 assesses the impact of any process on human health, ecosystem quality, and resource depletion. For a good overview of the methods used in Life Cycle Impact Assessment, the reader can refer to Finnveden et al. (2009) or Hellweg and Canals (2014).

2.2.1 Usage impact

The usage impact is the impact generated from the combustion, and production of fuel consumed by every machine in the system. The production impact per unit of fuel is defined as the impact generated by the production pathway from the oil well to the pump, while combustion impact per unit of fuel is the impact generated by the emissions released by the engine from consuming a unit of fuel. Total usage impact is simply the sum of the total combustion and production impacts of every machine, which can be easily calculated from simulated duration data, fuel consumption and emission rates, and per-unit production and emission impacts.

The per unit fuel production impact and emission impact can be obtained from Life Cycle Assessment software such as SimaPro (PRé Consultants, 2014), and GREET (Argonne National Laboratory, 2014). These applications come with databases such as ecoinvent (Ecoinvent, 2014) that contain data on production pathways for common materials and fuels. For most purposes, the impact values provided by these commonly used impact assessment software programs are an acceptable estimate.

2.2.2 Equipment impact

The equipment impact of a machine is the *scaled* impact of manufacturing the machine. The scaling factor is calculated by dividing the total simulation run-time by the machine's estimated average lifetime. The underlying principle is that the one-time impact of manufacturing a machine can be distributed evenly throughout its life. The total equipment impact of a system is therefore proportional to the mass of machinery in the system (assuming greater mass means higher manufacturing impact), and inversely proportional to system productivity and machine lifetime. A heavier system may end up having a lower equipment impact than a lighter system if the heavier system is able to complete its assigned tasks faster than the other system, or if the heavier system has machines with longer lifetimes.

The manufacturing impact of a machine can be calculated using material breakdown information contained in the bill of materials that is fed into impact assessment software. The reader can refer to Kwak et al. (2012) for more details.

2.2.3 Packaging impact

The last category, packaging impact, refers to the manufacturing impact of all packaging used by the system to package the cotton. In System A, the top and sides of each module are covered by a plastic tarp, while in System B, the modules are fully wrapped in plastic. The modules in System A are also much larger than the modules in System B.

2.3 Simulation parameters

A simulation of each of the cotton harvesting systems is used to obtain work mode durations for every machine that will be used to calculate usage and equipment impact. Packaging impact is simply a function of the number of modules produced at the end of the simulation. The work modes modelled for each machine type are shown in Table 2. Note that the "Transporter" refers to the tractor-pulled cotton cart in System A, and the tractor in System B.

Table 2. Machine types and respective work modes

Machine Type	Work Modes
Cotton stripper	Harvest, Idle
Transporter	Load/Unload, Transport, Idle
Module Builder	Working

Fuel consumption and emission rates for every work mode will need to be provided. In addition, the machine parameters shown in Figure 3 will need to be defined as well.

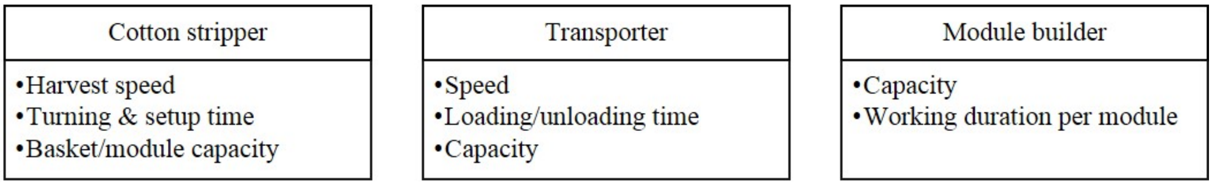

Figure 3. Required machine parameters for impact calculation

The basket (System A) or module (System B) capacity refers to the weight of ginned cotton that the basket or module can hold. The capacity of the transporter is specified as an integer multiplier of the cotton stripper's basket or module capacity. For example, if the cotton cart is able to take on at most 2 full baskets of cotton from the cotton stripper in System A, then the capacity of the cotton cart would be 2. In the case of System B, if the tractor is only able to move 1 module at a time, then its capacity would be 1. In a similar fashion, the capacity of the module builder is expressed as an integer multiplier of the capacity of the transporter. In other words, if the amount of cotton in a single module created by the module builder is equivalent to 3 dumps by the transporter, then the capacity of the module builder is equal to 3.

With the above parameters defined, the simulation model has everything it needs to model the movement and interactions of the machines in each system.

2.4 Simulation model logic

The first step in both simulations is to discretize the path of the cotton stripper into segments. The end of each segment is the point where the cotton stripper reaches full capacity (full basket in System A; completed module in System B) and the number of segments is given by taking the ceiling of the total amount of cotton in the field (yield times field area) divided by the capacity of the cotton stripper. Discretizing the path into segments simplifies the modelling by allowing the simulation to proceed segment by segment in a loop until the cotton stripper reaches the end of the last leg. Furthermore, the inner steps in each loop iteration can be customized to suit the characteristics of System A or B.

Figure 4 shows the steps in each iteration of System A's simulation. Note that at the end of each iteration, the cotton stripper and transporter are at the starting position of the subsequent segment; the cotton stripper is empty, and the transporter has its load increased by 1 count.

The arrival time of the cotton stripper at the end of the segment is simply current time plus leg distance divided by the harvest speed. The arrival time of the transporter at the end of the segment depends on whether it is full at the beginning of the iteration. If the transporter is full, then the transporter has to travel to the module builder, unload, and move to the end of the current segment. For this work, the transporter is assumed to move either vertically (along the field's length) or horizontally (along the field's breadth).

The module builder's total work duration is given by the number of modules generated by the module builder multiplied by the time taken to complete a single module.

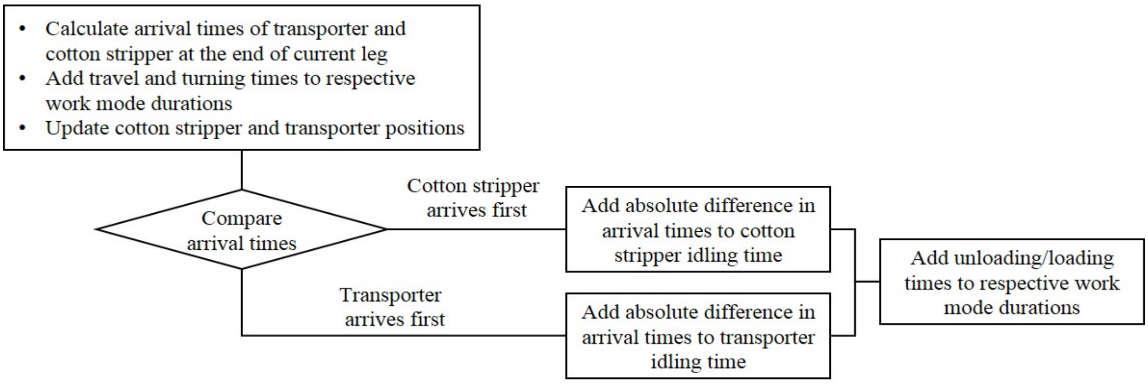

Figure 4. System A simulation iteration flowchart

Calculating work mode durations of the cotton stripper in System B is straightforward since the transporter and cotton stripper are de-coupled from each other — the cotton stripper does not require a transporter to be in attendance in order to unload a module. This also means that there is no cotton stripper or transporter idling time as is the case in System A. However, calculating transport mode duration of the transporter in System B is more complicated due to the capability of System B's cotton stripper to hold a completed module on its back, giving the driver some flexibility in choosing where to place the cotton modules along the cotton stripper's path. It is assumed in the simulation that the cotton stripper driver will drop each module along the cotton stripper's path as close as possible to the unloading point S.

System B's simulation starts off with an initialization step that finds the drop location of the very first module generated by the cotton stripper. Figure 5 shows the steps in each iteration *i* of the simulation after the initialization step. The position of the cotton stripper or the transporter is expressed as 2-dimensional coordinates (x_pos, y_pos), where x_pos is an integer corresponding to the harvesting pass that the cotton stripper is currently on. A harvesting pass is represented using solid arrows in Figure 1 and is numbered in increasing order from left to right, starting at 0. If the harvesting pass is even, then the cotton stripper is moving away from unloading point S, and if the harvesting pass is odd, the cotton stripper is moving closer to the unloading point. The y_pos coordinate is the vertical distance of the harvester from unloading point S, which has the coordinates (0, 0).

The start of each iteration after the initialization step is the point where the cotton stripper has just completed a new module. The simulation then calculates x_next_pos and y_next_pos, the coordinates of where the cotton stripper will complete the next module.

If the cotton stripper is currently moving away from the unloading point S (x_pos is even) then:

- If the next module comes out 2 passes or more later (x_next_pos > x_pos + 1) then the current module is dropped immediately at (x_pos, y_pos) or at the ending point of the next pass (x_pos + 1, 0) depending on which is closer to the unloading point S.
- If the next module comes out on the next pass, the current module is dropped at (x_pos, y_pos) or at (x_next_pos, y_next_pos) depending on which one is closer to point S.
- If the next module comes out on the same pass, the current module is dropped at (x_pos, y_pos).

If the cotton stripper is moving closer to the unloading point S (x_pos is odd) then:

- If the next module comes out on the next pass, the current module is dropped at the end of the current pass (x_pos, 0).
- If the next module comes out on the same pass, then the current module is dropped at (x_next_pos, y_next_pos).

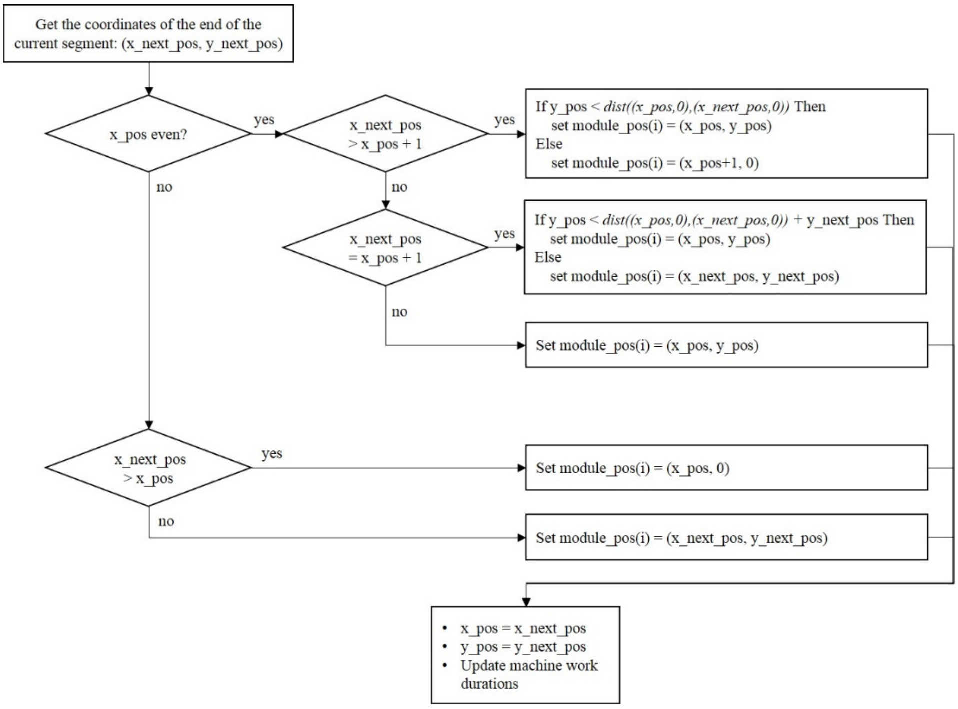

Figure 5. System B simulation iteration flowchart

3 RESULTS

The input parameters for both systems were obtained using estimates or information found in the technical manuals. Manufacturing impact calculations were based on the estimated materials composition of every machine. The dots in Figure 6 show the cotton stripper unloading points in System A, and the locations of the modules in System B. Note that the last unloading point or the last module is always located at the end of the cotton stripper's path at the upper right corner of the field because the cotton stripper "shuts down" once it reaches the end of its path.

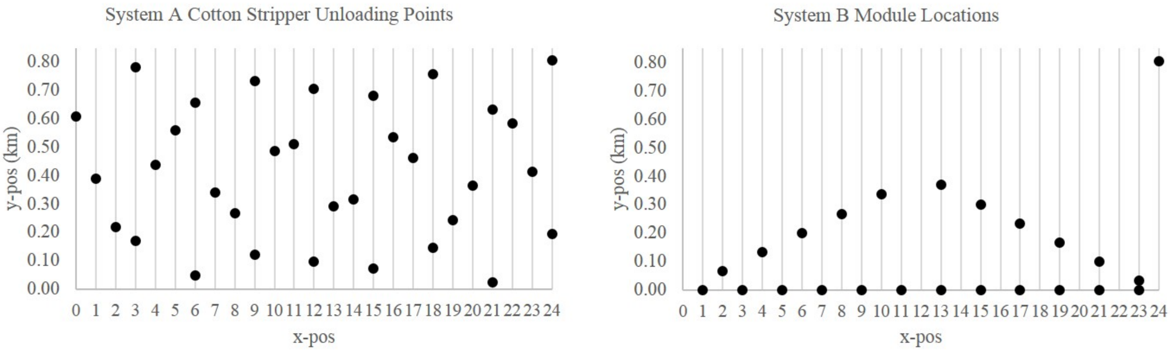

Figure 6. System A unloading points and System B module locations

Figure 6 shows that the ability of System B's cotton stripper to carry a completed module greatly reduced the distance travelled by the tractor since the modules can be dropped as close as possible to the unloading point (located at the origin).

The proposed framework also captured how "decoupling" the cotton stripper from the tractor in System B reduced the time spent on the field by the tractor. Unlike System A, the cotton stripper in System B can unload its cotton payload without requiring the presence of a transporter. This eliminates idling time arising from one machine waiting for the other to arrive. As a result, machine work mode durations were much smaller in System B than System A as shown in Figure 7.

Figure 7 also highlights the advantage of System B's multi-function cotton stripper design. The cotton stripper in System B was able to complete the harvesting and packaging task on its own, whereas the same two tasks were carried out by separate machines in System A with longer durations and consuming more fuel.

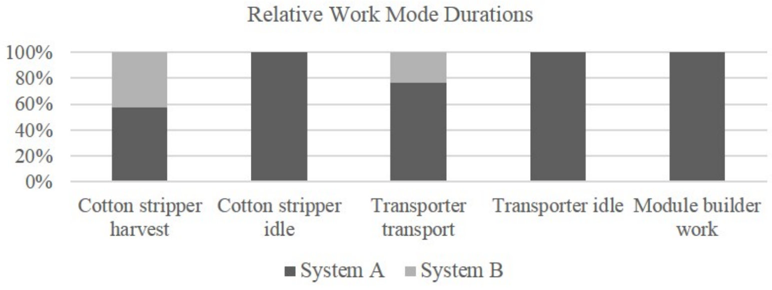

Figure 7. Relative work mode durations comparison

In terms of mass of machinery, the total weight of System A was around 3000kg greater than that of System B, which meant System A had a higher manufacturing impact than System B. In addition, System B was also more efficient than System A in completing the assigned tasks, so the EI-99 equipment impact of System B was lower than that of System A. However, in terms of contributions to total impact in both systems, equipment impact was much smaller than usage impact as shown in Figure 8. This is consistent with previous studies involving agricultural machinery such as Meisterling et al. (2009), Kwak et al. (2012), and Bortolini et al. (2014).

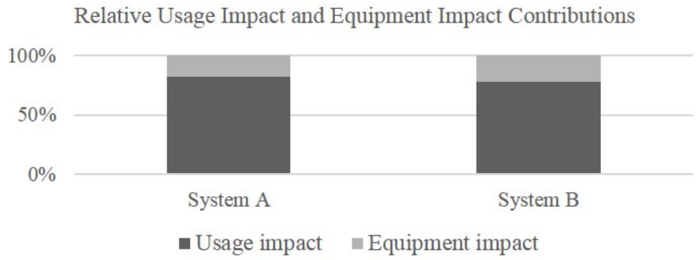

Figure 8. Usage impact and equipment impact contributions

System B generated less usage and equipment impact, but when it comes to packaging impact, System A had a much lower impact for two reasons. The first is that System A used less packaging material than System B because the modules in System A are much larger, and only the sides and top surfaces of modules are covered by the plastic tarp. In System B, the modules are smaller, and are completely wrapped in a plastic film to provide better protection from rain. The second reason is that the tarp in System A was assumed to be re-used twice, whereas each wrap in System B was assumed to be used once. As a result, the EI-99 packaging impact in System B was significantly higher than that of System A.

After summing up all the impact categories, the total impact generated by System B was still lower than System A, mainly due to System B's large reduction in usage impact compared to System A. The results showed that the increase in engine capacity and complexity of the cotton stripper design in System B was worthwhile since it led to increased harvesting efficiency and lower overall system mass. Specifically, the combination of a cotton stripper and a module builder in System B's cotton stripper design eliminated the need for a dedicated on-field module builder. Combining the two functions in one design also enabled the cotton stripper in System B to operate independently of the transporter, and the cotton stripper's additional ability of carrying a completed module greatly reduced the total distance travelled by the transporter.

The results generated by the proposed approach were then compared to the results from the old approach of using separate cotton stripper LCAs. It was assumed in the old approach that the lifetimes of both cotton strippers were the same, and that each cotton stripper spent 70% of its lifetime harvesting. Even after accounting for Cotton Stripper B's higher productivity, Cotton Stripper B still had the higher lifecycle impact when comparing stand-alone cotton stripper LCAs. The results highlighted how focusing on a single machine instead of the system could produce a skewed conclusion on the environmental impact of different cotton stripper designs.

The results also showed the important link between system efficiency and system environmental impact. Even though the cotton stripper in System B is much larger and used more fuel than System A's cotton stripper, System B's cotton stripper was able to greatly improve harvesting efficiency, which is why System B ultimately had the lower system environmental impact.

3.1 Exploring design alternatives in System B

Finally, the proposed framework was used to evaluate the impact of possible design changes to System B.

- Focus areas for design change

Figure 9 summarizes the impact distributions in both systems, and highlights the different focus areas for impact reduction in both systems. In System A, the bulk of the impact came from usage, so improvements such as more fuel-efficient transporters or a larger cotton stripper basket capacity would be effective in reducing total impact. In System B, the focus should be on reducing packaging impact, which accounted for a large portion of overall impact, by exploring design changes in bale density and wrapping material.

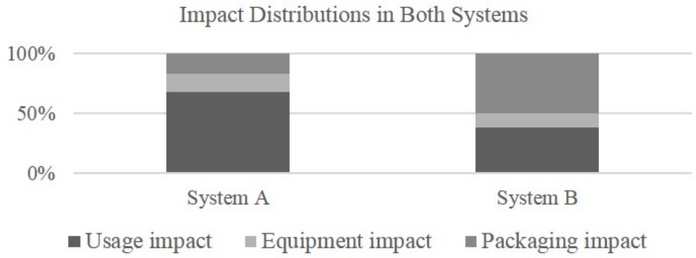

Figure 9. Impact distributions of both systems.

- Design change scenario 1: increasing bale density

Increasing the density of modules in System B is a promising design change that can pack more ginned cotton into every module, thereby reducing packaging use, and fuel usage by the transporter. The proposed framework was used to estimate the impact reduction brought about by an increase in System B's cotton module density by 20%. It was assumed that the wrap in its current form was able to deal with the increased strain, and that increased module weight had no impact on cotton stripper and transporter fuel rates. Figure 10 shows the placement of the modules in the current and modified systems. When the density was increased by 20%, the number of modules produced dropped from 24 to 20, leading to a 17% decrease in packaging impact. The increase in module density also brought about a 27% decrease in transporter impact due to fewer number of trips, and better module placement.

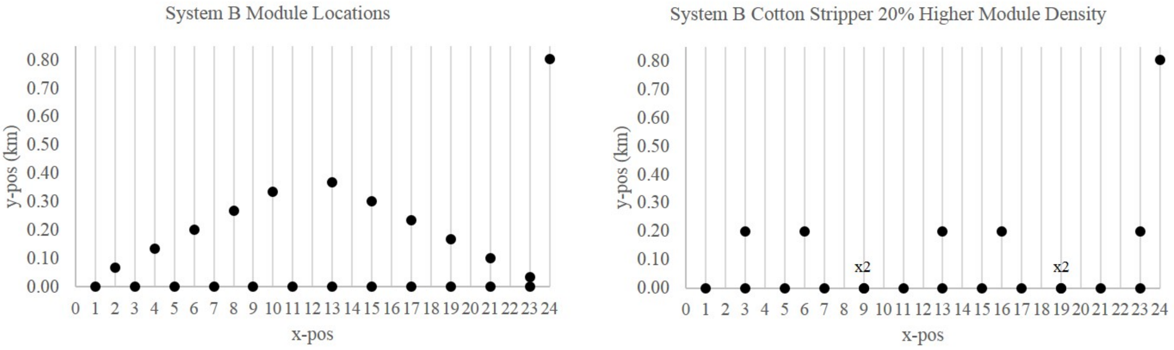

Figure 10. Module positions for current and modified System B

- Design change scenario 2: using new packaging material

As shown in Figure 9, the impact from packaging is approximately 50% of the total environmental impact for System B. This is due to the fact that the wrapping material has a high environmental impact and is not reusable. Potential design changes could be 1) to adopt a different wrapping material that is of less environmental impact and reusable, and 2) to enhance strength of the current wrapping material so that each module can be wrapped with smaller amount of wrapper (currently the modules are wrapped three times to insure integrity of modules).

4 CONCLUSION

This paper presented a framework for comparing the environmental impact of two cotton harvesting systems featuring two distinctive cotton stripper designs. The main motivation behind the proposed framework is to capture not only the direct environmental effects of design differences between the cotton strippers, but also the indirect effects of those differences on the supporting machinery.

The comparison results showed that the indirect effects can be significant, which is why comparing two single-machine LCAs would not give a fair result. In order to account for these indirect effects, the boundaries of the analysis should be expanded to the harvesting system. In this paper, the boundaries of the harvesting system were limited to the field, but it is possible under the proposed framework to expand the boundaries even further from the field to the cotton gin. This would give a more accurate assessment of the environmental impact of the plastic wrap in System B. One of the main benefits of using the wrap is that it is much better than the tarp at shielding cotton from the rain, which means less energy would be expended at the gin for drying cotton.

The framework was applied to a harvesting scenario with a single cotton stripper and a field of fixed size. A natural extension would be to include multi-harvester, varying field size scenarios for cotton, as well as other commercial crops, such as maize, which are also harvested using combine harvesters and grain carts. On an abstract level, harvesters and module builders can be thought of as processing centres for transporters. A harvester is "occupied" when harvesting, and becomes available when its grain tank becomes full. At that point, it waits for a transporter to arrive and transfer its grain cargo over to the transporter. Once the transporter is "served" by a harvester, it joins the queue at a module builder (or more generally, an on-field processing unit), unloads its cargo, and seeks out another available harvester. Since harvester and transporter movements follow a specific logic, it is possible to model their on-field movements using a discrete event simulation.

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