<u>Environmentally Responsible Drone Design: Sustainable Design and Manufacturing</u>

Learning Objectives

Students completing this case study will identify the challenges and benefits of sustainability decision making for design and manufacturing. The learning objectives of this case study are listed as follows:

- Students will use multi-perspectives for product design, considering requirements, functions, modules, product architectures, and suppliers, to develop environmentally responsible products.

- Students will perform a design decision-making process to integrate environmental issues into selection of product concepts and suppliers through the S-PASS (Sustainable Product Architecture and Supplier Selection) tool.

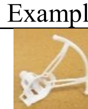
- Students will formulate their own design problems for development of environmentally responsible products.

Case Description

Drones and multi-copters are very familiar to consumers. While children play with remote controlled toy versions, some adults expect deliveries by drones. Company X is currently selling two types of drones: hexa-copters and quad-copters (See Table 1). Due to global regulations regarding the environmental impacts of products and companies, Company X is planning to upgrade its existing products through environmentally responsible design. The main objective of environmentally responsible drone design at Company X is to determine new product architectures and their suppliers while considering their possible environmental impacts. New drones should satisfy design requirements for minimal energy use and reduction in hazardous by-products/pollutants both from the manufacturing process and throughout useful life of drones. Modules in new drones should be provided by suppliers that are environmentally friendly in their operations (i.e., manufacturing and logistics). Key modules and components of the existing drone designs are provided in Table 1.

Company X has just signed a consulting agreement with your team to tap into your expertise in sustainable design and manufacturing. You are tasked with proposing new designs that are vastly improved in environmental sustainability performance over the current designs of drones. For facilitating the design task, your team will employ the Sustainable Product Architecture and Supplier Selection (S-PASS) tool provided in class (See Appendix). As a team, follow each phase outlined below and determine the input values to use within the S-PASS tool.

Table 1. Key Modules & Components of Two X-shaped Multi-Copters

Hexa-copter	No.	Module Name	Example
	1	Lower Shell	
	2	Knob	
	3	Upper Shell	
	4	Battery Cover	
	5	Propeller	
	6	Propeller Shield	
Quad-copter	**No.**	**Module Name**	**Example**
	1	Engine Cowling/ Propeller Shield	
	2	Lower Shell	
	3	Upper Shell	
	4	Propeller	

Phase 1: Sustainability Requirement Satisfaction of Existing Products

In this phase, design requirements, their associated functions, and existing modules of products are identified to calculate the satisfaction levels of requirements and functions in existing products. Current product architectures are then evaluated to determine whether the desired requirements and their associated functions are satisfied with the available modules in existing products.

-Team Tasks

Go to the "Phase1_Input" tab in the S-PASS tool (Excel) and follow the tasks shown below.

Task 1)

Requirements and functions identified for environmentally responsible drone design are specified below. Three requirements and five functions have been defined by Company X. Your team is asked to find three more desired requirements and their relevant functions, respectively.

<Requirements>

- R1: Energy efficiency
- R2: Durability

- R3: Low environmental impact
- R4: (e.g., use of renewable technology)
- R5:
- R6:

<Functions>

- F1: Transform energy to torque
- F2: Accept recharge from external electric power
- F3: Provide propulsion
- F4: Protect motors and rotors from external impacts
- F5: Allow for reuse or recycling
- F6: (e.g., transforming solar energy to electric energy)
- F7:
- F8:

Complete the requirement-function matrix using the table under Q1 (See Figure 1). Each requirement-function relationship represents the contribution probability of the function to the requirement. The matrix has been partially completed by engineers in Company X. However, your team can change the default contribution probability values if needed. Your team is required to enter new requirements and functions identified above for the matrix. Then, each cell value that is now empty are required to be determined. Contribution probabilities for the input cells can be estimated by considering their predefined descriptions provided in Table 2. Note that all empty cells of the table under Q1 should have values and the sum of all columns for each row should be 100%.

Q1) Please estimate to what extent each product function contributes to achieve each environmental sustainability requirement.

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		Function							
		F1: Transform energy to torque	F2: Accept recharge from external electric power	F3: Provide propulsion	F4: Protect motors and rotors from external impacts	F5: Allow for reuse or recycling	F6:	F7:	F8:
Requirement	R1: Energy efficiency	40%	20%	10%	0%	0%	0%	0%	0%
	R2: Durability	0%	0%	0%	60%	0%	0%	0%	0%
	R3: Low environmental impact	0%	10%	0%	0%	40%	0%	0%	0%
	R4:	0%	0%	0%	0%	0%	0%	0%	0%
	R5:	0%	0%	0%	0%	0%	0%	0%	0%
	R6:	0%	0%	0%	0%	0%	0%	0%	0%

* Each value indicates the contribution probability of the function to the requirement, a range from 0% to 100%.

Figure 1. Snapshot of Table for Q1 in Phase 1

Table 2. Interpretation of Contribution Probabilities

Probability	Description
0%	No contribution
~20%	Very low contribution
~40%	Low contribution
~60%	Moderate contribution
~80%	High contribution
~99%	Very high contribution
100%	Perfect contribution

Task 2)

Complete the requirement-function matrix using the table under Q2 (See Figure 2). Each function-module relationship represents a satisfaction level, indicating how well the existing module satisfies the function. The descriptions of satisfaction levels are shown in Table 3.

Q2) Please estimate to what extent each product module satisfies each product function.

	Module							
Function	M1: Lower Shell 1 (for Hexa-copter)	M2: Lower Shell 2 (for Quad-copter)	M3: Knob	M4: Upper Shell 1 (for Hexa-copter)	M5: Upper Shell 2 (for Quad-copter)	M6: Battery Cover	M7: Propeller	M8: Propeller Shield
F1: Transform energy to torque	5	0	0	0	5	0	0	0
F2: Accept recharge from external electric power	0	0	0	0	3	0	0	0
F3: Provide propulsion	4	0	0	0	4	0	5	0
F4: Protect motors and rotors from external impacts	3	4	5	2	1	4	0	4
F5: Allow for reuse or recycling	0	0	0	0	0	0	0	0
F6:	0	0	0	0	0	0	0	0
F7:	0	0	0	0	0	0	0	0
F8:	0	0	0	0	0	0	0	0

*Each satisfaction level is a range from 1 (poor) to 5 (very good) and has 0 if the module does not provide the function.

Figure 2. Snapshot of Table for Q2 in Phase 1

Table 3. Interpretation of Satisfaction Levels

Level	Description
0	No relation
1	Very poor in satisfaction
2	Poor in satisfaction
3	Fair in satisfaction
4	Good in satisfaction
5	Very good in satisfaction

Modules considered in the current drone designs are specified below.

<Modules>

- M1: Lower Shell 1 (for Hexa-copter)
- M2: Lower Shell 2 (for Quad-copter)
- M3: Knob
- M4: Upper Shell 1 (for Hexa-copter)

- M5: Upper Shell 2 (for Quad-copter)
- M6: Battery Cover
- M7: Propeller
- M8: Propeller Shield

The matrix has been partially completed by engineers at Company X (However, your team can change the default satisfaction level values if needed). Your team is required to estimate each cell value that is empty. Make your own assumptions to estimate the satisfaction level of each module for the identified functions. For example, you may consider that M1, M2, M4, and M5 in the current products are very poor for their reuse and recycling potential (these would have a value of "1" in the matrix). Note that all the empty cells of the table under Q2 should have values from 0 to 5.

Task 3)

The two drones described in Table 1 will be used as foundations for new drone development at Company X. Please complete the table under Q3 (See Figure 3) based on the product information provided by Company X in Table 1.

Q3) Please identify the module composition of current products

		Product Architecture	
		P1: Hexa-copter	P2: Quad-copter
Module	M1: Lower Shell 1 (for Hexa-copter)	0	0
	M2: Lower Shell 2 (for Quad-copter)	0	0
	M3: Knob	0	0
	M4: Upper Shell 1 (for Hexa-copter)	0	0
	M5: Upper Shell 2 (for Quad-copter)	0	0
	M6: Battery Cover	0	0
	M7: Propeller	0	0
	M8: Propeller Shield	0	0

*1 (used), 0 (not used)

Figure 3. Snapshot of Table for Q3 in Phase 1

- Team Discussion

Click the "See Phase 1 Results" button in the Phase1_Input worksheet to view the results of Phase 1 for the existing products. Based on the information that your team inputs, the S-PASS tool converts "To what extent modules satisfy functions" to "To what extent existing product architectures satisfy functions" and "To what extent functions contribute to achieve requirements" to "To what extent existing products satisfy requirements." These are easily expressed through matrix multiplications. The matrix under Q2 ($M_{\text{function-module}}$) is multiplied with the matrix under Q3 ($M_{\text{module-architecture}}$) to generate the matrix ($M_{\text{function-architecture}}$), representing function satisfaction levels in product architectures (See Eq. 1). Then, the matrix under Q1 ($M_{\text{requirement-function}}$) is further multiplied with the generated matrix ($M_{\text{function-architecture}}$) to obtain the matrix to represent requirement satisfaction levels of product architectures (See Eq. 2).

$$M_{function-module} \times M_{module-architecture} = M_{function-architecture} \tag{1}$$

$$M_{requirement-function} \times M_{function-architecture} = M_{requirement-architecture} \tag{2}$$

Requirements and functions that have average satisfaction levels lower than "Fair" in any existing product are considered to be unsatisfactory in the current product design. Unsatisfied requirements and functions are shaded in red, and their associated modules are specified in the Phase 1 Output worksheet. These modules in the current drone products should be replaced with new modules to be considered for use in new products.

ACTION ITEM:

Discuss how the unsatisfactory modules should be redesigned to achieve the requirements and functions not currently achieved by the existing drone designs. What information and activities would be helpful to redesign the current drones?

Phase 2: New Module and Supplier Filtering

In Phase 1, your team has found the existing modules of the current drones that do not adequately satisfy the identified requirements. To replace these existing modules, alternative modules and their related supplier information are compiled and evaluated with specific attention to environmental indicators in Phase 2. Table 4 shows the list of alternative modules and their suppliers. These new modules provide enhanced functionality with reasonable cost to replace the existing modules.

Company X has evaluated the alternative modules and suppliers using several environmental indicators, as shown in Tables 5 and 6, respectively.

Table 4. New Modules and Suppliers

Current Module	Current Supplier	Alternative Module	Main Feature	New Supplier
M1	E1	A1	excellent embedded motor, recharge with USB or battery, reinforced plastic body cover, solar cell energy transfer sensor, and extensive add-on options (camera, controllable legs, etc.)	S1
		A2	excellent embedded motor, reinforced plastic body cover	S2
		A3	excellent embedded motor, recharge with USB or battery, reinforced plastic body cover, solar cell energy transfer sensor, and limited add-on options	S1
M2	E1	A4	reinforced plastic body cover	S1
		A5	reinforced plastic body cover	S2
M3	E1	A6	reinforced plastic body cover	S1
		A7	reinforced plastic body cover	S2
M4	E2	A8	reinforced plastic body cover	S2
		A9	reinforced plastic body cover	S3
M5	E2	A10	excellent embedded motor, recharge with USB or battery, reinforced plastic body cover, solar cell energy transfer sensor, and extensive add-on options (camera, controllable legs, etc.)	S2
		A11	excellent embedded motor, recharge with USB or battery, reinforced plastic body cover, solar cell energy transfer sensor, and limited add-on options	S2
		A12	excellent embedded motor, reinforced plastic body cover	S3
M6	E2	A13	reinforced plastic body cover	S1
		A14	reinforced plastic body cover	S3
M7	E2	A15	reinforced plastic body cover	S1
		A16	reinforced plastic body cover	S3
M8	E3	A17	reinforced plastic body cover	S1
		A18	reinforced plastic body cover	S3

Table 5. Evaluation of Environmental Indicators for the Alternative Modules Considered

Alternative Module	Hazardous Material Use: Possibility to satisfy RoHS (Level: 1 = poor ~ 5 = very good)	Recyclability: Recycling Rate (0% ~ 100%)	Renewable Material Use: Satisfaction Level of Using Renewable Materials (Level: 1 = poor ~ 5 = very good)
A1	5	70%	4
A2	4	50%	1
A3	5	90%	5
A4	5	90%	5
A5	3	50%	1
A6	5	90%	5
A7	4	10%	1
A8	5	90%	5
A9	1	70%	1
A10	4	90%	5
A11	5	90%	4
A12	1	10%	3
A13	5	90%	5
A14	1	10%	2
A15	2	90%	5
A16	5	30%	3
A17	4	80%	5
A18	1	40%	3

Table 6. Evaluation of Environmental Indicators for the Alternative Suppliers Considered

Supplier	ISO 14001: Possession of ISO 14001 Certification (Yes: 1, No: 0)	Use of Recycled Materials: Capability of Using Recycled Material (Level: 1 = poor ~ 5 = very good)	Environmentally Friendly Packaging: Packaging Recycling Rate (0% ~ 100%)
S1	1	5	90%
S2	1	4	90%
S3	0	1	20%

Your team has been asked to find appropriate alternative modules and their suppliers to replace the unsuitable modules identified in Phase 1. Perform the following tasks based on the information provided in Tables 4, 5, and 6.

-Team Tasks

Click “Go to Phase 2” button in the “Phase1_Output” worksheet, and follow the tasks shown below using the “Phase2_Input” worksheet.

Task 1)

Your team needs to input all the alternative modules and their suppliers that can replace the inadequate modules identified in Phase 1. Complete the table under Q1 (See Figure 4) based on the information specified in Table 4. You will see a drop-down list for your input when you click on an empty cell in the matrix table under Q1.

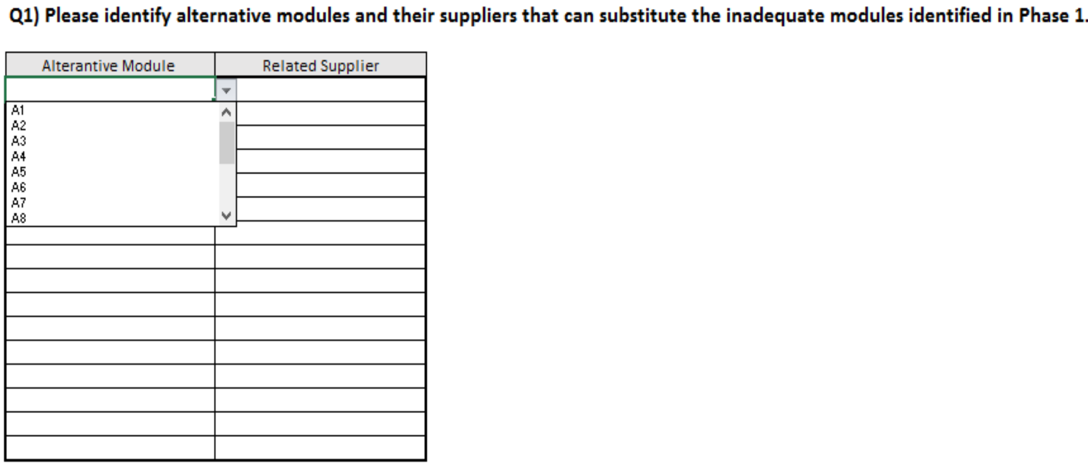

Figure 4. Snapshot of Table for Q1 in Phase 2

Task 2)

Set your desired threshold value for each environmental indicator in the matrix table under Q2 (See Figure 5). You will see a drop-down list of values for each environmental indicator when you click on an empty cell in the matrix table under Q2.

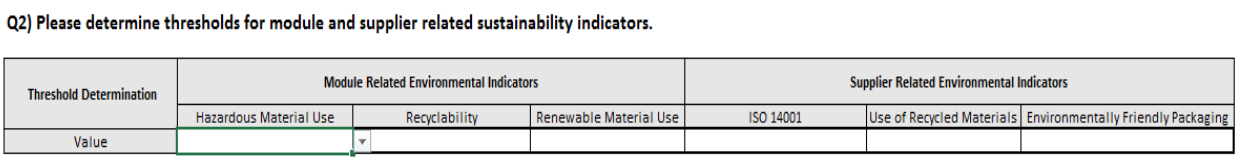

Figure 5. Snapshot of Table for Q2 in Phase 2

- Team Discussion

Click on “See Phase 2 Results” button in the Phase2_Input worksheet to view the results of Phase 2. The S-PASS tool filters alternative modules and suppliers using the thresholds for the environmental indicators that your team inputs. Only modules and suppliers that are evaluated as higher than and/or equal to thresholds in all associated environmental indicators are accepted for new drone designs. If the supplier of an accepted module is not accepted in the supplier filtering, the module is not considered for new drones. In the same way, if an accepted supplier provides rejected modules, then those modules are also not considered for use in new drones.

Based on the information of filtered modules and suppliers, a final list of alternative modules and their suppliers is shown in the worksheet. Note that all alternative modules and suppliers might be excluded during the module and supplier filtering steps if your team set very high thresholds for the indicators. On the other hand, all alternative modules would be accepted if your team set too low indicator thresholds. In either of these cases, your team should need to adjust the threshold values to allow an acceptable level of filtering to narrow down the options.

ACTION ITEM:

Discuss the appropriate threshold values with your team members. What are the implications of having a large (very small) set of options?

Phase 3: Product Architecture and Supplier Selection

In this phase, the functional satisfaction levels of new modules are identified to update the initial functional satisfaction matrix. Then, all possible product architectures that can be configured with existing and new modules are generated to create an initial product architecture set. Final architecture candidates and their suppliers are selected by evaluating the initial architectures with requirement satisfaction.

-Team Tasks

Click on "Go to Phase 3" button in the "Phase2_Output" worksheet, and complete the tasks shown below in the "Phase3_Input" worksheet.

Task 1)

Complete the matrix table under Q1 (See Figure 6). First, type the existing modules that are not required to be replaced and the new modules identified from Phase 2 for the first row of the table. Note that at least one (current or alternative) module for each module type of the defined 8 module types should be included in the first row. For example, type A1 and A2 in different columns of the first row if the alternative modules of M1 are both accepted for new drone design.

Q1) Please estimate how well each product module satisfies each product function.

		Module									
Function	F1										
	F2										
	F3										
	F4										
	F5										
	F6										
	F7										
	F8										

*Use satisfaction level 1 (poor) -5 (excellent)

Figure 6. Snapshot of Table for Q1 in Phase 3

Then, estimate the functional satisfaction levels using the matrix table under Q1 based on your own assumptions and the information provided for the new modules in Table 4. The functional satisfaction levels of the existing modules should be the same as those that you input for Phase 1. If there are empty columns in the table after all the modules' functional satisfaction levels are determined, make all the remaining empty cells have "0" values.

Task 2)

Complete the supplier-module matrix using the matrix table under Q2 (See the example in Figure 7) based on the information provided for the suppliers in Table 4. Note that all the remaining empty cells should have "0" values.

Q2) Please identify each module's supplier.

Supplier	A1	A3	A4	A6	A8	A10	A11	A13	A15	A17
E1	0	0	0	0	0	0	0	0	0	0
E2	0 1	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0
S1	1	1	1	1	0	0	0	1	1	1
S2	0	0	0	0	1	1	1	0	0	0
S3	0	0	0	0	0	0	0	0	0	0

*1 (related), 0 (not related)

Figure 7. Snapshot of Table for Q2 in Phase 3

Task 3)

Your team is asked to develop alternative drone designs for the Hexa-copter and Quad-copter. Define product architectures in the table under Q3 (Figure 8) with the identified modules for new drone design. Note that all the required component types for each drone type, described in Table 1, should be configured in its product architecture through the identified modules. Define three product architectures by combining relevant modules. Each product architecture should represent the Hexa-copter or the Quad-copter drone type and have different combination of the considered modules.

Q3) Please define each architecture with modules.

Module	Architecture 1	Architecture 2	Architecture 3
A1	1	0	0
A3	0 1	1	0
A4	0	0	1
A6	1	1	0
A8	1	1	0
A10	0	0	1
A11	0	0	0
A13	1	1	0
A15	1	1	1
A17	1	1	1

*1 (related), 0 (not related)

Figure 8. Snapshot of Table for Q3 in Phase 3

-Team Discussion

Click on "See Phase 3 Results" button in the "Phase3_Input" worksheet to view the results from Phase 3. Based on the information that your team inputs in Phase 3, the S-PASS tool provides: 1) average functional satisfaction levels for new product architectures, 2) average requirement satisfaction levels for new product architectures, and 3) suppliers selected for new product architectures. The average satisfaction levels of requirements and functions in new product architectures are obtained based on matrix multiplications shown in Eqs. 1 and 2.

ACTION ITEM:

Discuss the results of Phase 3 by comparing the results of Phase 1. How do you interpret the results? Have you successfully derived environmentally sustainable designs and suppliers for the existing products?

Appendix

Sustainable Product Architecture and Supplier Selection (S-PASS)

The Sustainable Product Architecture and Supplier Selection (S-PASS) tool is designed to guide users to identify sustainable product architectures and their suppliers. The use of S-PASS within this platform aims to: 1) enhance students' class activities relevant to sustainable product and service design modules, and 2) provide an easy to use and effective tool to enable students to determine product architectures and Original Equipment Manufacturer (OEM) suppliers with consideration of possible environmental impacts.

An overview of S-PASS is illustrated in the figure below. The S-PASS basically employs a matrix propagation system, which constructs and uses a series of overlapping matrixes, to derive a final solution through matrix operations starting from the rows in the initial matrix to columns in the last matrix. Input information regarding new part modules and suppliers in consideration of sustainable design requirements and proper environmental impact is processed through the matrix system to obtain acceptable sustainable product architectures and their suppliers.

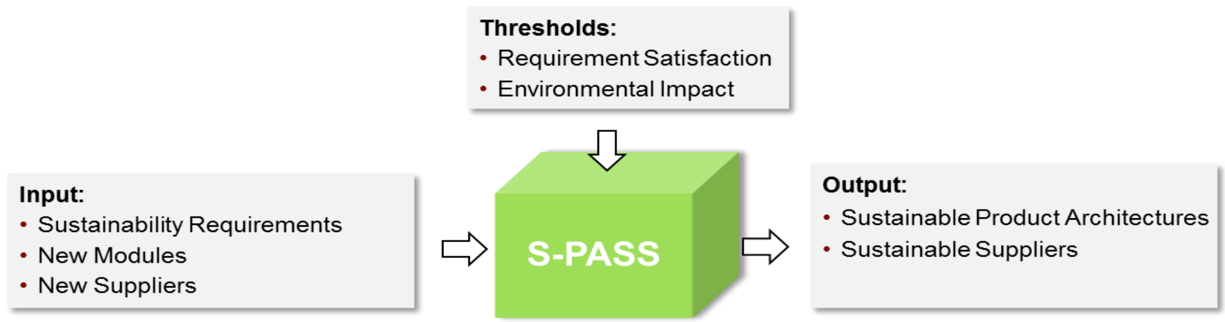

Figure 9. Overview of S-PASS

The S-PASS consists of three main phases and the descriptions of each phase are as follows:

- **Phase 1**: Sustainability Requirement Satisfaction of Existing Products
  Relationships between sustainable design requirements and their associated functions, and between functions and module types are identified. Then, existing products are evaluated to find whether the functions and requirements are satisfied with the available modules in these products.

- **Phase 2**: New Module and Supplier Filtering
  With respect to current modules that do not satisfy the sustainability requirements, alternative modules and their supplier information are compiled and evaluated with specific attention to environmental indicators.

- **Phase 3**: Product Architecture and Supplier Selection
  With new modules and suppliers filtered through Phase 2, functional satisfaction levels of all modules and all possible suppliers are identified. Then, all possible product architectures that can be configured with these modules are generated to create an initial product architecture set. Final architecture candidates and their suppliers are selected by evaluating the initial architectures for requirement satisfaction.