Dairy CAP

Application of Design of Experiments to project modeling

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Dairy CAP
Application of Design of Experiments

- **Design of experiments (DOE)** is a systematic method to determine the relationship between factors affecting a process and the output of that process.
  - In other words, it is used to find cause-and-effect relationships.
- Here, I use DOE to analyze input parameters for models of dairy operations. Our goals include:
  - Identifying superior systems at the whole farm/ multi-practice levels.
  - Understanding variability within the context of location and changing climate conditions.

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- Some DOE concepts
  - **Two types of factors**
    - Controllable factors: Parameters that can be controlled (e.g., the type of manure storage used, the type of tillage used)
    - Uncontrollable factors: Parameters that cannot be controlled or are too expensive to control (e.g., the weather)
  - **A full factorial design** executes the full set of model runs over all combinations of factors.
  - Taguchi's DOE method plans experiments using orthogonal arrays
    - to conduct the minimal number of experiments which could give the full information of all the factors that affect the output of interest.

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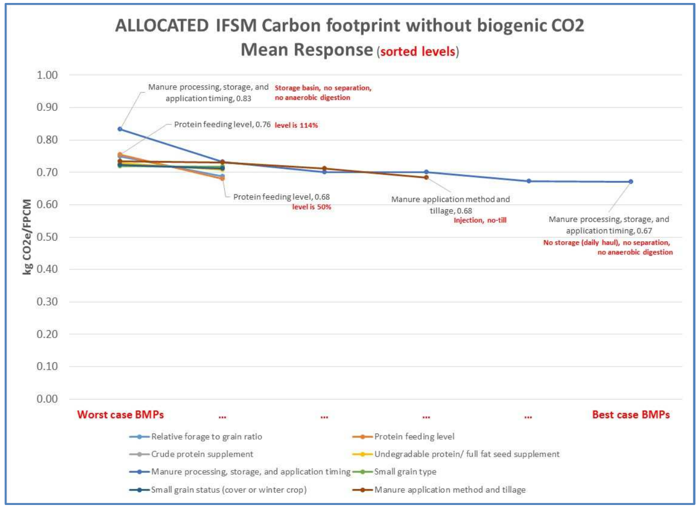
- **DOE** can be applied to the Dairy CAP modeling effort in 4 steps:
  1. **Identify the output(s)** of interest (e.g., dairy farm contribution to climate change).
  2. **Identify management practices and uncontrollable conditions** to be evaluated and the levels at which each will be modeled, while ensuring factor independence.
  3. **Design inner and outer arrays** for the management practices and uncontrollable conditions respectively. These arrays dictate the model scenarios to be run.
  4. **Run the model scenarios, and analyze mean responses and variability.**

	Parameter	Level 0	Level 1
1	Corn silage/alfalfa ratio **(2 levels)**	1:1	3:1
2	Forage level **(2 levels)**	0.65	0.5
3	Digestibility (as NDF) **(2 levels)**	low NDF	high NDF
4	Feed efficiency (as kg Milk/kg DMI) **(2 levels)**	1.5	1.63 or 1.65
5	Fat **(2 levels)**	3.75%	5.5%
6	Protein content **(2 levels)**	17%	14%

…



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Step 1: Identify the output(s) of interest (e.g., dairy farm contribution to climate change).

- For example, GHG emissions that match the USEPA's National GHG Inventory dairy farm emissions.
  - US inventory data homepage is at http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

	EPA GHG Inventory Item	Units	Notes
Enteric fermentation	Enteric fermentation	CH4, kg	
Manure management	Manure management methane emissions	CH4, kg	
	Direct manure management nitrous oxide emissions	N2O, kg	
	Indirect manure management N2O Emissions Due to Volatilization	N2O, kg	
	Indirect manure management N2O Emissions Due to Leaching and Runoff	N2O, kg	
Feed production	Mineral Soil N2O Emissions	N2O, kg	
	Direct N2O Emissions Due to Drainage of Organic Soils	N2O, kg	
	Indirect Soil N2O Emissions Due to Volatilization	N2O, kg	
	Indirect Soil N2O Emissions Due to Leaching and Runoff	N2O, kg	
	Additional changes in net N2O emissions from the application of sewage sludge	N2O, kg	
	Additional changes in net N2O emissions for enrollment as CRP land	N2O, kg	
	Lime application carbon dioxide emissions	CO2, kg	
	Urea application carbon dioxide emissions	CO2, kg	
	CO2 emissions from Mineral Soil Organic C Stock Changes	CO2, kg	For Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland.
	Soil Organic C Stock Changes Due to Drainage of Organic Soils	CO2, kg	"

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Step 2: Identify management practices and uncontrollable conditions to be evaluated and the levels at which each will be modeled, while ensuring factor independence.

LARGE FARM Management Practices (according to BMP Minutes DairyCAP annual meeting March 1_2_2016d)

		Parameter	Level 0	Level 1	Level 2	Level 3	Level 4
Feed management	1	Corn silage/alfalfa ratio	1:1	3:1			
	2	Forage level	0.65	0.5			
	3	Digestibility (as NDF)	low NDF	high NDF			
	4	Feed efficiency (as kg Milk/kg DMI)	1.5	1.63 or 1.65			
	5	Fat	3.75%	5.5%			
	6	Protein content	17%	14%			
Manure processing and storage	7	Manure processing and storage	Lagoon no separation= liquid manure, no processing and 6 month storage basin (lagoon scenario)	Liquid-solid separation (screw press) and storage basin	Anaerobic digestion, and storage basin	Anaerobic digestion, liquid-solid separation and storage basin (New York farm)	Storage basin covered (lower cost cover - this does not include the cover with methane collection as that will be similar to the digestion scenario) sealed with flare
Crops	8	Manure application schedule	50% fall/50% spring (preplant)	50% fall/50% spring with cover crop + corn silage	spring with 25% of annual manure applied in-season with cover crop	Fall and spring application with harvested winter crop rye, terminated in the Spring + corn silage	
	9	Tillage	Surface applied, not incorporated (or late incorporation) with tillage after 72 hours	Surface applied incorporated the same day	Surface application no-till	Injection no till	

This is called the inner array for things we can control

Note that the "manure application schedule" needs to be altered in an effort to achieve independence.

- Manure that is hauled daily is not stored.
- Also it seems that the cover and winter crop specification can be specified independently of the manure application schedule.

Uncontrollable conditions, large and small farms

		Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
1	Locations	Twin Birch Farm	Wisconsin/Arlington	Pennsylvania/ Lancaster			
2	Climate scenarios	Priority climate scenario 178	Priority climate scenario 140	Priority climate scenario 3	Priority climate scenario 83	Priority climate scenario 11	Priority climate scenario 163

This is called the outer array for things we cannot control

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– **Alterations from the original Dairy CAP BMP list**

- First, the small grain status was separated out, with 2 parameters at 2 levels covering (a) the small grain as wheat or rye and (b) the small grain as a winter or cover crop
- Second, the application timing was added to "manure processing and storage" so that the length of storage can be matched to the application schedule.

		Parameter	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9
Feed management	1	Corn silage/alfalfa ratio **(2 levels)**	1:1	3:1								
	2	Forage level **(2 levels)**	0.65	0.5								
	3	Digestibility (as NDF) **(2 levels)**	low NDF	high NDF								
	4	Feed efficiency (as kg Milk/kg DMI) **(2 levels)**	1.5	1.63 or 1.65								
	5	Fat **(2 levels)**	3.75%	5.5%								
	6	Protein content **(2 levels)**	17%	14%								
Manure processing and storage and application timing	7	Manure processing and storage *and application timing* ***(10 levels)***	*6 month storage basin, no separation, no anaerobic digestion,* ***50% fall/ 50% spring application***	*6 month storage basin, separation, no anaerobic digestion,* ***50% fall/ 50% spring application***	*6 month storage basin, no separation, anaerobic digestion,* ***50% fall/ 50% spring application***	*6 month storage basin, separation, anaerobic digestion,* ***50% fall/ 50% spring application***	*6 month covered basin with flare, no separation, no anaerobic digestion,* ***50% fall/ 50% spring application***	*9 month storage basin, no separation, no anaerobic digestion ,* ***75% fall application from storage/ 25% spring application as daily haul***	*9 month storage basin, separation, no anaerobic digestion ,* ***75% fall application from storage/ 25% spring application as daily haul***	*9 month storage basin, no separation, anaerobic digestion ,* ***75% fall application from storage/ 25% spring application as daily haul***	*9 month storage basin, separation, anaerobic digestion ,* ***75% fall application from storage/ 25% spring application as daily haul***	*9 month covered basin with flare, no separation, no anaerobic digestion ,* ***75% fall application from storage/ 25% spring application as daily haul***
Crops	8	*Small grain type* ***(2 levels)***	*Wheat*	*Rye*								
	9	*Small grain cover or winter crop* ***(2 levels)***	*Cover + corn silage*	*Winter + corn silage*								
	10	Tillage **(4 levels)**	Surface applied, not incorporated (or late incorporation) with tillage after 72 hours	Surface applied incorporated the same day	Surface application no-till	Injection no till						

The result is 10 parameters,
- **8 at 2 levels**
- **1 at 4 levels**
- **1 at 10 levels**

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Step 3: Design inner and outer arrays for the management practices and uncontrollable conditions respectively. These arrays dictate the model scenarios to be run.

- For the management practices, step 2 presents **10 parameters, 8 at 2 levels, 1 at 4 levels, and 1 at 10 levels.**
  - The **full factorial design** is therefore 10,240 (=10*4*2^8) model runs **JUST for the inner array**.
  - For the large farms with 3 locations and 6 climate scenarios in the outer array, the full factorial design represents 184,320 model runs.
  - Instead, a mixed-level orthogonal array is used to identify 40 inner array model runs is used (OA(40, 2^8 4^1 10^1))
  - This means that when the outer array is considered, we will need 720 (=40*3*6) model runs for the large farms. **THIS IS STILL A LOT!!!!!!!**

Inner array for the Dairy CAP Large Farms

- For the inner array, OA(40, 2^8 4^1 10^1) was prepared from OA(40, 2^19 4^1 10^1) using *expansive replacement*
  - The OA was developed by Agrawal and Dey 1982 as well as Wang and Wu, 1991
  - The OA was identified at http://neilsloane.com/oadir/ and is available at http://support.sas.com/techsup/technote/ts723_Designs.txt
  - Expansive replacement and other aspects of OAs are described by Stufken at https://www.newton.ac.uk/files/seminar/20110905171518151-152916.pdf

```
2^19 4^1 10^1      n=40
0000000000000000000033
0000101011110011010 20
```

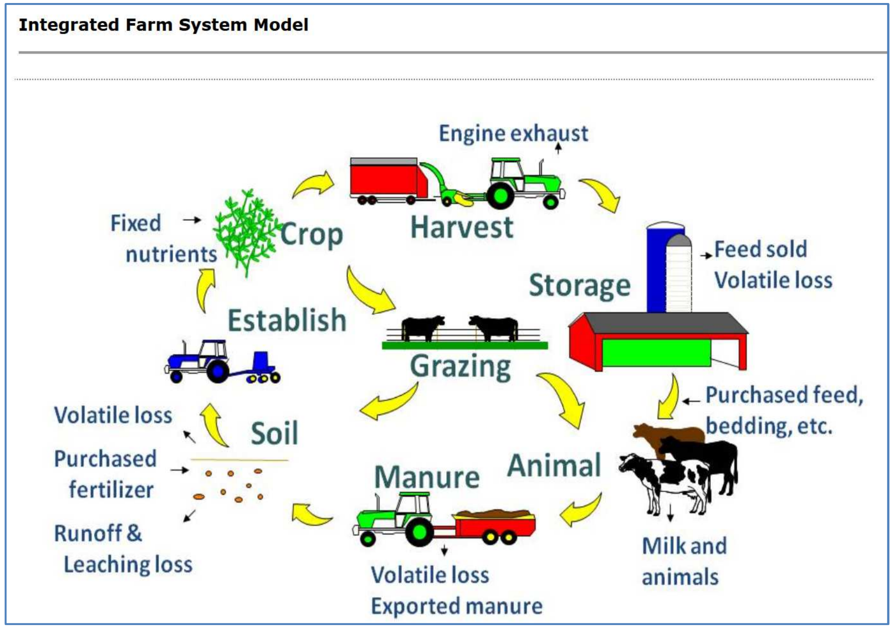
IFSM Management Practices (inner array with 40 model runs)

			BMP system 1	BMP system 2	BMP system 3	BMP system 4	…	BMP system 39	BMP system 40
Feed management	**1**	Corn silage/alfalfa ratio **(2 levels)**	1:1	3:1	3:1	1:1		1:1	3:1
	2	Forage level **(2 levels)**	0.65	0.65	0.5	0.65		0.5	0.5
	3	Digestibility (as NDF) **(2 levels)**	low NDF	low NDF	high NDF	high NDF		high NDF	high NDF
	4	Feed efficiency (as kg Milk/kg DMI) **(2 levels)**	1.5	1.63 or 1.65	1.63 or 1.65	1.63 or 1.65		1.5	1.63 or 1.65
	5	Fat **(2 levels)**	0.0375	0.055	0.0375	0.0375		0.0375	0.055
	6	Protein content **(2 levels)**	0.17	0.17	0.14	0.14		0.14	0.14
Manure processing and storage and application timing	**7**	Manure processing and storage *and application timing* ***(10 levels)***	6 month storage basin, no separation, anaerobic digestion, 50% fall/ 50% spring application	9 month covered basin with flare, no separation, no anaerobic digestion, 75% fall application from storage/ 25% spring application as daily haul	6 month storage basin, no separation, no anaerobic digestion, 50% fall/ 50% spring application	9 month storage basin, no separation, no anaerobic digestion, 75% fall application from storage/ 25% spring application as daily haul		9 month covered basin with flare, no separation, no anaerobic digestion, 75% fall application from storage/ 25% spring application as daily haul	6 month storage basin, no separation, anaerobic digestion, 50% fall/ 50% spring application
Crops	**8**	*Small grain type* ***(2 levels)***	Wheat	Rye	Wheat	Rye		Wheat	Rye
	9	*Small grain cover or winter crop* ***(2 levels)***	Cover + corn silage	Cover + corn silage	Cover + corn silage	Winter + corn silage		Cover + corn silage	Cover + corn silage
	10	Tillage **(4 levels)**	Surface application no-till	Surface applied incorporated the same day	Surface applied, not incorporated (or late incorporation) with tillage after 72 hours	Surface application no-till		Injection no till	Surface applied, not incorporated (or late incorporation) with tillage after 72 hours

This sets us up for
Step 4: Run the model scenarios, and analyze mean responses and variability….

IFSM example

- The following IFSM example is INSPIRED by the DairyCAP BMP list and started with Al's Twin Birch model
  - It is VERY important to note that this is intended to be an example, I only made changes in the GUI, and **certainly the IFSM Dairy CAP modeling team can do better:)**



IFSM example

Step 1: Identify the output(s) of interest (e.g., dairy farm contribution to climate change).

- Here I use IFSM's ALLOCATED "Carbon footprint without biogenic CO2" in kg CO2e/kg FCMP
- HOWEVER, I have identified a set of outputs that get us pretty close to the items in the USEPA's GHG inventory

Step 2: Identify management practices and uncontrollable conditions to be evaluated and the levels at which each will be modeled, while ensuring factor independence.

- Here I did my best to match what was available in the IFSM GUI to the DairyCAP BMPs.
- Note that "feed management" was altered in an effort to match the options available through the IFMS GUI and does not really capture what the team BMPs.
- Note that the "manure application schedule" was altered in an effort to achieve independence.
  - Because I could not determine how to model "75% fall application from storage/ 25% spring application as daily haul" using the IFSM GUI, the ten levels have been reduced to 6, such that the first 5 cover "50% fall/ 50% spring application" and the sixth represent 100% daily haul.

IFSM example

Step 2: Identify management practices and uncontrollable conditions to be evaluated and the levels at which each will be modeled, while ensuring factor independence.

	DOE parameter	DOE param no	IFSM Dialog box	IFSM Tab	IFSM Subgroup	IFSM Units	IFSM Parameter	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Feed management	Relative forage to grain ratio	1	Animal and Feeding Ir	Feeding	Ration constituents	high/low	Relative forage to grain ratio	high	low				
	Protein feeding level	2	Animal and Feeding Ir	Feeding	Ration constituents	% of NRC recom	Protein feeding level	114%	50%				
	Crude protein supplement	3	Animal and Feeding Ir	Feeding	Ration constituents		Crude protein supplement	Soybean meal, 48%	Canola seed meal				
	Undegradable protein/ full fat seed sup.	4	Animal and Feeding Ir	Feeding	Ration constituents		Undegradable protein/ full fat seed :	Soybean seed, roast	None				
Manure processing, storage, and application timing	Manure processing, storage, and application timing	5						*Storage basin, no separation, no anaerobic digestion*	*Storage basin, separation, no anaerobic digestion*	*Storage basin, no separation, anaerobic digestion*	*Storage basin, separation, anaerobic digestion*	*Covered tank or basin, no separation, no anaerobic digestion*	*No storage (daily haul), no separation, no anaerobic digestion*
	Note that the Twin Birch primary manure is liquid-slurry		Manure Information	Primary Handling	Storage		Period	6 month storage	6 month storage	6 month storag	6 month storage	6 month storage	No storage or daily hauling
	(5-7% DM) and the Twin Birch secondary manure is solid		Manure Information	Primary Handling	Storage		Storage type	Top-loaded lined ea	Top-loaded lined ea	Top-loaded line	Top-loaded lined eai	Covered tank or basin	
	(20% DM)		Manure Information	Primary Handling	Storage	yes/no	Anaerobic digester	no	no	yes	yes	no	no
			Manure Information	Secondary Handling	Collection and hauling	%	Portion handled in secondary systen	0	0.25	0	0.25	0	0
			Manure Information	Import/ Export	Export		Form	Raw manure	Separated solids	Raw manure	Separated solids	Raw manure	Raw manure
Crops	Small grain type	6	Crop and Soil Informa	Small Grain	Un-named		Small grain crop	wheat	rye				
	Small grain status (cover or winter crop)	7	Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 1 name	Established with gra	No operation used				
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 1 starting date	19-Sep					
	Manure application method and tillage	8						*Surface applied, not incorporated (or late incorporation) with tillage after 72 hours*	*Surface applied incorporated the same day*	*Surface application no-till*	*Injection no till*		
	Note that a box spreader is used for solid manure.		Machine Information	Tillage/ Planting	Operation		Primary manure handling machine t	Large slurry tank spi	Large slurry tank sp	Large slurry tar	Truck mounted slurry tank injector		
	Note that for conventional till, the Alfalfa operations		Machine Information	Tillage/ Planting	Operation		Primary manure handling tractor siz	220 hp tractor	220 hp tractor	220 hp tractor	No tractor used		
	are the same as in Al's IFSM model but have been		Manure Information	Primary Handling	Collection and hauling		Incorporation by tillage	Within two days	Same day	No incorporatio	No incorporation		
	moved down 1 (operation 1 is operation 2 here)		Manure Information	Secondary Handling	Collection and hauling		Incorporation by tillage	Within two days	Same day	No incorporatio	No incorporation		
	because operation 1 in IFSM is the only 1		Machine Information	Tillage/ Planting	Operation		Plowing machine type/size	Coulter-chisel plow,	Coulter-chisel plow	None	None		
	that can be used for the small grain cover crop		Machine Information	Tillage/ Planting	Operation		Plowing tractor size used	220 hp tractor	220 hp tractor	No tractor usec	No tractor used		
			Machine Information	Tillage/ Planting	Operation		Field cultivation machine type/size	Field cultivator, 23 f	Field cultivator, 23	None	None		
			Machine Information	Tillage/ Planting	Operation		Field cultivation tractor size used	134 hp tractor	134 hp tractor	No tractor usec	No tractor used		
			Machine Information	Tillage/ Planting	Operation		Row crop planting machine type/siz	Corn planter, 16-rov	Corn planter, 16-ro	Zone till corn p	Zone till corn planter, 12-row (9.1 m)		
			Machine Information	Tillage/ Planting	Operation		Row crop planting tractor size used	134 hp tractor	134 hp tractor	134 hp tractor	134 hp tractor		
			Machine Information	Tillage/ Planting	Operation		Drill seeding machine type/size	Grain drilll, 12 ft (3.	Grain drilll, 12 ft (3	No-till grain dri	No-till grain drill, 15 ft (4.6 m)		
			Machine Information	Tillage/ Planting	Operation		Drill seeding tractor size used	100 hp tractor	100 hp tractor	134 hp tractor	134 hp tractor		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 2 name	Moldboard/chisel p	Moldboard/chisel p	Alfalfa seeding	Alfalfa seeding		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 2 starting date	15-Apr	15-Apr	27-Apr	27-Apr		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 3 name	Field cultivator/ con	Field cultivator/ co	No operation u	No operation used		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 3 starting date	25-Apr	25-Apr				
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 4 name	Field cultivator/ con	Field cultivator/ co	No operation u	No operation used		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 4 starting date	25-Apr	25-Apr				
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 5 name	Field cultivator/ con	Field cultivator/ co	No operation u	No operation used		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 5 starting date	25-Apr	25-Apr				
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 6 name	Alfalfa seeding	Alfalfa seeding	No operation u	No operation used		
			Tillage and Planting Ir	Alfalfa	Sequence of operations		Operation 6 starting date	27-Apr	27-Apr				
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 1 name	Moldboard/chisel p	Moldboard/chisel p	Corn planting	Corn planting		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 1 starting date	1-Apr	1-Apr	5-May	5-May		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 2 name	Field cultivator/ con	Field cultivator/ co	No operation u	No operation used		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 2 starting date	25-Apr	25-Apr				
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 3 name	Corn planting	Corn planting	No operation u	No operation used		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 3 starting date	5-May	5-May				
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 4 name	No operation used	No operation used	No operation u	No operation used		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 4 starting date						
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 5 name	No operation used	No operation used	No operation u	No operation used		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 5 starting date						
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 6 name	No operation used	No operation used	No operation u	No operation used		
			Tillage and Planting Ir	Corn	Sequence of operations		Operation 6 starting date						

IFSM example

Step 3: Design inner and outer arrays for the management practices and uncontrollable conditions respectively. These arrays dictate the model scenarios to be run.

- For the management practices, step 2 presents **8 parameters, 6 at 2 levels, 1 at 4 levels, and 1 at 6 levels**
  - The full factorial design is therefore 1,536 (=4*6*2^6) IFSM model runs for the inner array.
  - For the large farms with 3 locations and 6 climate scenarios in the outer array, the full factorial design represents 27,648 IFSM model runs (so not including the small farm runs).
  - Instead, a mixed-level orthogonal array is used to identify 24 inner array model runs is used (OA(24, 2^6 4^1 6^1) adapted from Wang and Wu, 1991)
  - This means that when the outer array is considered, we will need 432 (=24*3*6) IFSM model runs for the large farms. **THIS IS STILL A LOT!!!!!!!**

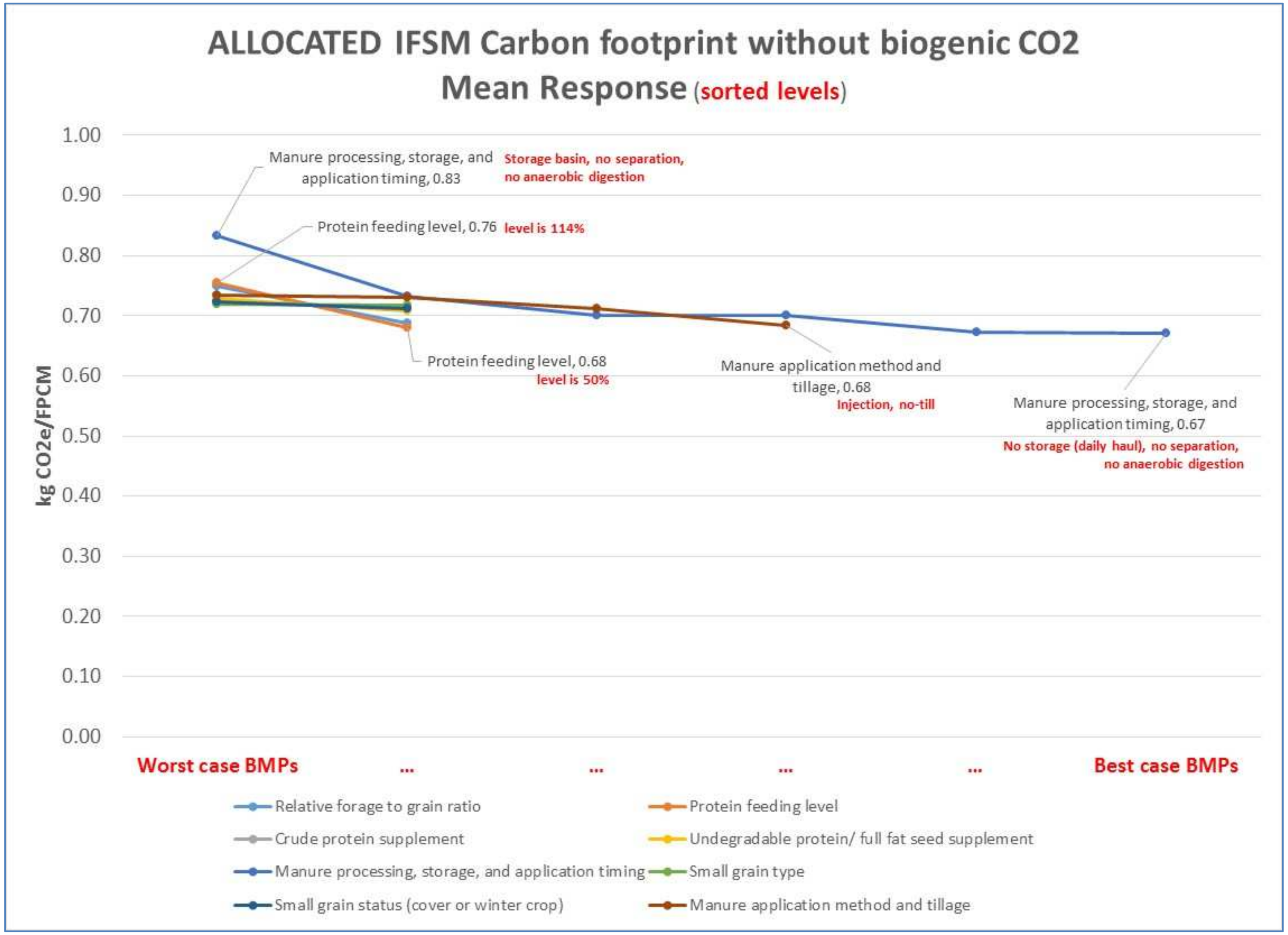
– **Step 4:** Run the model scenarios, and analyze mean responses and variability.

Note that values changed from the original Twin Birch files to ensure all runs proceed without error
- SP forage harvester was changed to Large SP forage harvester
- All machine information equipment quantities were multiplied by 4
- The primary manure storage system average diameter was increased from 60.7 to 80 m
- Under Tillage and Planting Information, grass and soybean operations set to "No operations used"

Note that keeping these the same for all means sometimes there is more capacity than needed.

IFSM example

- For each level of each controllable factor, the **mean response** is the average output for all scenarios using that level for that controllable factor. For IFSM's ALLOCATED "Carbon footprint without biogenic CO2" in kg CO2e/kg FCMP…



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- The combination of best case BMPs results in a footprint of **0.56 kg CO2e/kg FCMP**, **down from 0.74 kg CO2e/kg FCMP** in Al's Twin Birch Model.
- Notice that I have not run any scenarios using the alternative locations and climate files. Doing this will tell us more about how robust the systems are.
- Any questions?