Modeling and Analysis for Sustainable Development Based on Collaborative Control Theory (CCT)

PRISM Center
Production, Robotics, and Integration Software for Manufacturing and Management

“Knowledge through information; Wisdom through collaboration”

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Motivation / Objective

- **Sustainability challenges:** Strategically reduce waste, energy, hazards; overcome cultural / political differences; sustain profitability and viable communities

- **Sustainability decisions:** Complex, interdependent, need advanced modeling and control techniques, effective collaboration
## What is sustainability?

Many definitions, three common bottom lines of sustainability:

**Environmental, Social, and Economic sustainability**

<table>
<thead>
<tr>
<th>Source</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Oxford English Dictionary, 1989</td>
<td>Capacity to keep a person or community from failing; maintain at the proper level; support life and nature with needs</td>
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<td>Rosenbaum, 1993</td>
<td>Using methods, systems, materials that would not deplete resources or harm natural cycles</td>
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<td>Vieria, 1993</td>
<td>Development that looks at a site's natural land, water, and energy resources as integral aspects of the development</td>
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<td>Valentin &amp; Spangenberg, 2000</td>
<td>Sustainable development is structured around four thematic imperatives: economic, social, environmental, and institutional, and six inter-thematic links, one for each bi-dimensional interconnection</td>
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<td>Swiss Federal Statistical Office, 2005</td>
<td>Three main elements: Social solidarity; Economic efficiency and Ecological responsibility; and 45 postulates classified in 20 categories</td>
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<td>U.N. General Assembly, 2005</td>
<td>The reconciliation of environmental, social and economic demands - the &quot;three pillars&quot; of sustainability</td>
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<td>Villeneuve, 2006</td>
<td>Four dimensions define sustainable development: Ecological, economic, social, and ethical.</td>
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Sustainability and Collaboration

Collaboration, & Cyber-support for effective collaboration
Sustainability issues in various industries

Common to all sustainable industries:
- A process of continuous improvement
- Assess/reassess areas to improve sustainability performance
- Sustainable construction industry: Construction sites and production facilities for construction suppliers
- Sustainable transportation industry: Combine societal needs, efficiency, and impacts on the natural environment
- Environmentally conscious and product recovery manufacturing:
  - Life cycle analysis; Material selection; Design for environment + for disassembly + for recycling
  - Reverse logistics
  - Remanufacturing and disassembly
## 2012 Production Planning & Control Special Issues

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<th>Special Issue Topic</th>
<th>Sample Article Topics</th>
<th>Authors</th>
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<td><strong>Sustainable Mfg.</strong>&lt;br&gt;Garetti, Mummolo, Taisch (eds.)&lt;br&gt;PPC 23(2-3)</td>
<td>Environmental sustainability value cycle</td>
<td>Barber, Beach, Zalikiewski</td>
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<td></td>
<td>Sustainable supply chain design</td>
<td>Abdalla, Diabat, Simchi-Levi</td>
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<td>Environmental costing for sustainable mfg.</td>
<td>Cagno, Micheli, Trucco</td>
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<td>Sustainable management of end-of-life systems</td>
<td>Godichaud, Tchangani, Peres, Iung</td>
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<td>Reverse supply chain and product recovery</td>
<td>Loomba, Nakashima</td>
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<tr>
<td><strong>Sustainable Collaborative Networks – Case Studies</strong>&lt;br&gt;Matos &amp; Boucher (eds.)&lt;br&gt;PPC 23(4)</td>
<td>Carbon friendly supply chains</td>
<td>Jaegler, Burlat</td>
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<td>Clothing industry sustainable supply networks</td>
<td>MacCarthy, Jayarathne</td>
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<td>RFID adoption in Italian silk industry</td>
<td>Quetti, Pigni, Clerici</td>
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<td>Fuzzy model for food safety risk assessment</td>
<td>Wang, Li, Shi</td>
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<td>Collaborative networks for product services</td>
<td>Lelah, Mathieux, Brissaud, Vincent</td>
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<td>Collaborative network success and trust</td>
<td>Becket, Jones</td>
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Collaboration is Key
CCT, Collaborative Control Theory, is useful

Value of Collaboration (VOC)

- Effective collaboration can overcome sustainability challenges:
  - Resolve conflicts, negotiate agreements
  - Prevent errors
  - Fault tolerance by teaming and back-up
  - Optimize sharing (of transportation, resources), reuse, etc.

- CCT comprises six design principles plus a common analytic framework to enable different systems achieve better sustainability through collaboration.

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- Velasquez & Nof: Ch. 88, Springer HB of Automation, 2009
CCT principles, and CSS, Collaboration Support Systems

1. **CRP**: Collaboration Requirement Planning
2. **PARK**: Parallelism + KISS: “Keep It Simple, cyber System!”
3. **CEDP**: Conflict & Error Detection and Prognostics
4. **FTT**: Fault-Tolerance by Teaming
5. **JLR**: Join/ Leave/ Remain in a collaborative network
6. **LOCC**: Lines Of emergent Command and Collaboration

- HUBs (“Internet on steroids”) enable CI, Collaborative Intelligence focused on improving human ability to collaborate effectively

Collaboratorium Initiative for CI [Purdue, 08] = **CCT + CSS**

- **Access** + Interaction Science e.g., human visualization
- **Domain Knowledge** + Content and Tools e.g., NanoHub.org
HUB-CI emerging advantages

• Better than existing HUBs based on CCT, HUB-CI is focusing on improving human collaboration through e-collaboration tools and services, by:

1. Significantly enhanced synthesis and integration of knowledge and discoveries
2. Understanding the dynamics of interactive-collaborative research work
3. Timely delivery of critically needed discoveries and shared knowledge
Emerging global networks (hubs/clouds) to trade/adapt/engage/learn diverse ideas through collaboration with sustainability

...challenges:

- Cross-culture capabilities?
- Multi-cultural interaction and infrastructures?
- Challenged web-based applications?
- Asynchronous multimedia?
Innovation HUB-CI

1. **Cross-culture capabilities** – There is a need for effective tools and ontologies for communicating across multiple languages and cultures through text, illustrations, and multimedia tools.

2. **Multi-cultural interaction and linking multi-cultural infrastructures** – Human, social and environmental factors necessitate support and incentive mechanisms to promote engagement for dialog and knowledge sharing.

3. **Challenged web-based applications** – Working with limited bandwidth and constrained computing infrastructure capabilities (e.g., in remote regions needing human support).

4. **Asynchronous multimedia interactive collaboration** – “emails” and non-real-time tele-meetings are required so people from different time zones can virtually meet “off line” while progressing effectively to meet time-constrained goals with minimal delays.
Decision support models, algorithms and protocols* based on CCT for sustainability enhancement in real cases

1. Sustainability decision support protocol (S-DSP)
   a. Sustainable supplier selection problem
   b. Sustainable delivery scheduling problem
2. Collaborative production line control protocol (CPLCP)
3. Collaborative demand and capacity sharing protocol (CDCSP)

* Protocol: Distributed algorithm/procedure of algorithms for workflow optimization (vs. Protocol agreements)
Decision Support Protocol - S-DSP (Seok & Nof, 2011)

Model: Decisions for complicated sustainability conflicts; it consists of three sub-parts: (1) Disruption Analysis (DA), (2) Negotiation Management (NM), (3) Knowledge Management (KM)

**Characteristics**

1. The importance of risk analysis
2. Conflicts among different objectives and participants
3. Numerous scattered information

**Sub-protocols**

- Disruption Analysis (DA)
- Negotiation Management (NM)
- Knowledge Management (KM)
Disruption Analysis (DA)

- Prediction and management of possible disruptions related with specific sustainability issue, based on historical information and similar case studies.
- DA can choose and use appropriate analysis tools for risk analysis: fuzzy logic, stochastic methods including MCMC, forecasting methods, and Bayesian models.

Negotiation Management (NM)

- For better decision making, negotiations for different objectives of participants in supply networks are processed.
- **Multiple Criteria Decision Aids** (MCDA); Weighted Sum Model (WSM), Weighted Product Model (WPM), Value Analysis (VA), fuzzy logic, Genetic Algorithm (GA) and Artificial Neural Networks (ANN) are applied for negotiations.
S-DSP (Cont.)

Knowledge Management (KM)

- Constant updating and analysis of databases and accurate connections between these databases and other sub-protocols:
  - **DB1**: Relevant case studies and regulations/agreements of specific sustainability issues are organized according to the type of related members and characteristics of issues.
  - **DB2**: Various methodologies which help the decision making process are classified into two classes -- strategic and mathematical (operational) methods.
  - **DB3**: All other related and critical information, especially from outsources, are saved. Historical data of each member’s demands, orders, accidents, violations, and specific events are saved here.
### CCT principles in Decision Support Protocol, S-DSP

| JLR | With multiple parties, additional constraints and parameters of existing, negotiated formulations need to be considered.  
|     | JLR analysis and decisions lead to add (or remove) "players" parameters, so the projected sustainability can be estimated effectively. |
| LOCC | Practically all industries are affected by sustainability goals, with mutually useful dynamic information flow between them, e.g., environmental policy changes.  
|     | LOCC models use these information flows to negotiate and develop collaborative formulations and emergent organization changes. |
| CRP | Multiple sustainability criteria must be considered effectively and in parallel based on the characteristics of each party and within various situations.  
| PARK | CRP/PARK are helpful when new constraints are added. Within CRP-II, the formulation can be revised in real time, adapted to temporal changes and constraints. |
Applying S-DSP in Supply Networks

Supply Network

Sustainability issues*

Manufacturers
- Select energy resource for manufacturing
- Select outsourcing partner/suppliers
- Select the ingredients and process type
- Select disposal and reuse policy
- Schedule manufacturing

Distribution centers
- Transportation scheduling
- Select the type of fuel of trucks
- Select packaging type
- Assign the human resource
- Set up the human rights and labor policy

Retailers
- Order scheduling
- Stock-out problem handling
- Set up the shipment policy
- Set up Fair business operating principles
- Set up the customer management policy

Information databases

DB1
Case study information

DB2
Decision supporting methodologies

DB3
Related Knowledge

S-DSP: Sustainability - Decision Support Protocol
DA: Disruption Analysis
KM: Knowledge Management
NM: Negotiation Management

Customers

Purdue University

PRISM Lab/Purdue
S-DSP for Sustainable Supplier Selection

KM
- Support DA and NM by three databases
- Update the databases

DA
- Select related disruption factors
  - Each supplier’s uncertainty
  - Market uncertainty
- Analyse each supplier’s failure rate using statistical data analysis
- Analyse the market fluctuation using scenario-based reasoning

NM
- Select possible necessary negotiations
  - Tradeoff among sustainability factors
  - Contract requirements between the company and each supplier
  - Consideration of the government policies
- Solve the tradeoff among factors using the Multi-objective function or fuzzy logic
- Analyse the constraints and requirements between company and each supplier using the cost/prices analysis
- Analyse the effect of contracts based on government policies using the cost/prices analysis

Select the best supplier
S-DSP for Sustainable Delivery Scheduling

DA
• Consider the demand fluctuation

NM
• Decide whether manufacturers A and B cooperate or not during each period
  • CRP-II and JLR provide useful guidelines for the work of NM

KM
• Request order quantity from each retailer (demand)
• Available number of trucks and capacity of each
• Location information of manufactures and retailers
• Related costs, delivering cost, and other costs
Data / Knowledge Bases

**DB1**
- Case studies on each participants
- Case studies on each sustainability issue

**DB2**
- Strategic method
- Mathematical method

**DB3**
- Historical data
- Regulations, government policies
- Related sustainability information (Environmental, social and economic)
Case: Collaborative delivery scheduling and sustainability
Significant impacts of employing S-DSP and CCT

a. Air pollutant (by delivery process) decreased

b. Employee workload decreased

Both reduced by between 9.7% and 20.6% with 12.8% average improvement

c. Manufacturers’ trucks utilization increased on average by 19.3%

d. Manufacturers’ additional profit -- always non-negative

Seok et al., ARC, 2012
Case: Impacts of employing S-DSP and CCT

16. Decrease of pollutant per product (occurred by production process)

17. Decrease of manufacturers’ lost sales

18. Decrease of manufacturers’ idle capacity

19. Manufacturers’ additional profit
Collaborative Production Line Control Protocol - CPLCP

(Levalle et al., 2012)

- Streamlining sustainable raw materials procurement processes
- Rethinking distribution footprints, strategies, and alliances
- Increasing manufacturing performance and efficiency for economic sustainability

Model building blocks: Process and buffer models
## CCT Principles in CPLCP

| CRP I | • Machines and buffers are collaborative resources  
• Collaborative resources’ goal is to keep low WIP inventory while maximizing throughput, regardless of the system status  
• The best static control policy is defined for every possible combination of process states, assuming that this condition is the steady state |
| CRP II | • Production rates and buffer levels adjustment based on the system’s evolution (actual or forecasted by the *Early Conflict Detection Tool*)  
| CEDP | • Early Conflict Detection Tool (ECDT) predicts which machine is most likely to be the next to fail (based on historical information of time between failures)  
• Conflict forecasting along with a prevention methodology enables the collaborating agents to take actions to minimize the impact of such conflict on the lines’ performance |
| FTT | • ECDT coupled with a conflict prevention methodology provide the rules for machines to “help each other” overcome failures, thus making the production line more stable. |
Workflow Simulation with CPLCP

1. Define the best static control policy for each possible system state
2. Scan for system state change
3. Are all machines operational?
   - Y: Set operational processes speeds according to CRP-I, balanced system status
   - N: Set buffer target to maximum capacity in buffers preceding failed equipment
4. Update information on the ECDT Tool to estimate system state duration
5. Set operational processes speeds according to CRP-I information for system status
6. Adjust buffer levels and process speeds based on ECDT Tool information
Tissue Converting Line Control with CPLCP

• Production line control under uncertainty conditions
• Highly adaptive and anticipatory methodology that enables collaboration between the different components of the lines to overcome failures and maintain sustainable throughput while keeping WIP low.
Demand & Capacity Sharing Protocol - CDCSP

(Seok & Nof, 2012)

- Enhance companies’ sustainability in the long term
  - Improve resource utilization by minimize idle capacity
  - Increase customer satisfaction by reducing lost sales

General process

Order acceptance → Start the production

Lost sales/idle capacity have usually occurred?

No → Collaborative scheduling

Yes → CDCSP
CCT Principles in CDCSP

**JLR**
- Collaborative network organization can be formed based on the concept of JLR principle
- The success of any business integration is a function of the degree of cooperation among the integrated sub-systems. Especially for complex, highly distributed and collaborative sub-systems, integration and cooperation become more necessary.

**CPR I**
- Depend on the characteristics of manufacturers, capacity provider and order provider are differentiated appropriately.

**CPR II**
- Depend on the change of demand based on market trend and customer behavior, new collaborative partnership can be formed.
Workflow Simulation with CDCSP

- Mfg 1
- Mfg 2
- Mfg 3
- Mfg 4

Calculation of expected profit of possible collaboration

Find the best partner and send the offer

Find other alternative

Negotiation

Is it accepted?

Success?

Confirm collaborative planning

Update
Conclusions

- Sustainability is essential and complex, but must be achievable
- Some progress achieved in modeling, decision processes and algorithms, measurement, control models and control theory
- Collaborative mechanisms and information sharing are needed for better sustainability communication, planning, and control
- Collaborative intelligence over high-performance computing is emerging.
Acknowledgement

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References

References