Logistics Supply Network Structures for Industry 4.0

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IGSTC Workshop on
"Strategies and Concepts for Advanced Manufacturing"
New Delhi
January 23-24, 2014

Agenda

1. Industry 4.0
2. Multi-Agent-Systems for Logistics Management
3. PlaSMA Case Studies
Goals of the 4. Industrial Revolution

Individual Products
- Mass individualisation of products and production processes with a lot size of 1

Increasing Flexibility and Robustness of the Production Processes
- Increased flexibility versus disturbances and outages
- Change of product properties even during the production process

Better Transparency and Data Quality
- Integration of material, information and control flows

Resource Productivity and Efficiency
- Process simulation and optimisation before and during the start-up of manufacturing plants and processes as well as of complete value creation networks

Global ICT Trends

- Moore’s Law (1965): The number of transistors on an integrated circuit will double every 18 months.
  - The performance of processors doubles every 18 months.

- Marc Weiser (1991): “In the 21st century the technology will move into the everyday, the small and the invisible.”
  - Mainframe ⇒ PCs ⇒ Mobile devices ⇒ CPS ⇒ Smart things

- Further ICT: Identification devices, sensor networks, communication networks, positioning systems, user interfaces ...

Cyber-Physical Systems as drivers of the Internet of Things and Services
Industry 4.0

The 4. Industrial Revolution is enabled and accelerated by CPS as Innovation Drivers

Properties of CPS in production systems:
• Locally/globally networked and real-time sensors
• Global intelligent networks of self-X, context aware systems with dynamic boundaries
• Control of these Systems of Systems by Human-System-Cooperation

Example: Industry 4.0 – Resilient Factory

Resilient factories must allow for robust and situative changes for just-in-time logistics and production with an optimal capacity utilisation.

Disruptive aspects:
• Fast retrofit of the production line corresponding to the actual order
• Integration of individual process steps in the production line: e.g., integration of planning and control
• Plug & Produce capabilities of the production modules

Enabler:
• Interface standards for universal combinable production modules
• Function- and capabilities-oriented description of the logistics and production processes
• Software changeability
• Continuous production data evaluation and simulation across all levels of order status and production layout
Global Economic Trends towards Resilient Logistics

**Globalisation**

- Globally distributed logistic networks
  - Production networks (Virtual Enterprises),
  - Multistage supply networks,
  - Distribution networks
  - Increasing complexity of logistics systems

**Customer-centric strategies**

- Shift from sellers’ markets to buyers’ markets
  - Increasing transport volume, atomisation of deliveries, increasing delivery frequencies
  - Increasing dynamics of logistics processes

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The 1000 $ question:

Which ICT architectures for Industry 4.0 production and logistics?
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Which ICT architectures for Industry 4.0 production and logistics?

The digital representatives of real-world objects obtain a certain degree of autonomy enabling them to make decisions by themselves according to their goals set.
**Definition of Autonomous Control**

*Autonomous control* describes a process of decentralised decision making in a non-hierarchically structured logistics system.

*Autonomous control* requires interacting elements of a non-deterministic concurrent system which are able to make decisions by themselves without external instructions (except their goals)

*Autonomous control* aims towards higher robustness and positive emergence of the global system by a distributed and flexible management of dynamics and complexity.

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**Holistic Perspective on Logistics**

Logistics system

- Decision system
- Information system
- Execution system

Task layers within the CRC 637

- Organisation and management
- Informatics methods and ICT
- Material flows and logistic processes

- Human
- Mass
- Energy
- Information

Technical System
The IoT for Autonomous Cooperating Objects

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Multi-Agent Systems as an Evolution of the Object-Oriented Paradigm

Properties

- Event- or activity-based system behaviour, even proactive
- Inherently distributed model
- High Scalability
- Discrete time model for an event-based simulation
- Dynamical model changes: Agents can enter and leave a simulation and can have arbitrary interactions
- Model of emerging phenomena

Individual Agent Interaction

- Individual resource consumer agents negotiate with providers
- Competition between consumers
  - Each agent optimizes its own payoff
  - Individual learning of best activities
Multiagent Team Interaction

Agents cooperate in teams
- Team optimizes common welfare of members
- Single member as team representative (*manager*)
- Manager interacts with providers on behalf of members
- Manager learns best activities for the team

Different teams compete with each other

Adaptation Methods for Dynamic Knowledge

- Real-world logistics is highly dynamic and requires robust and context-sensitive decision making.
- Knowledge acquisition *for* and *by* software agents presupposes relevance assessment and learning abilities.
- Resource-bound agents need to dispose of irrelevant information
- Integration of knowledge management and machine learning methods for adaptive agents
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3. PlaSMA Case Studies

PlaSMA - Multiagent-based Simulation Environment

- Based on the FIPA-compliant agent platform JADE
  - Java-implementation of the abstract FIPA-architecture
    - Communication, Management, Message transport
  - contains Agent Communication
    - Interaction protocol
    - Communication acts, Content languages
  - offers predefined behavior patterns for agents

- Extended JADE to
  - distributed simulation (multiple core, multiple hosts)
  - discrete event simulation (synchronizes the model time in the simulation)
  - modeling of logistic scenarios and their visualization
PlaSMA Simulation System

- Logistic world model specified by OWL ontology
- Logistic objects and services implemented as interacting software agents
- Easy transfer from simulation to deployment
- Synchronization service for distributed simulations
- Result logging in database
- Experiment analysis tools
- Online scenario visualization

PlaSMA World Model

- Ontology-based specification of the simulated world
  - participants, organization structures, physical objects, infrastructure
  - PlaSMA-agents simulate objects and participants in the simulated world
- OWL-DL ontology language
  - Terminological Knowledge (TBox, the domain schema)
  - Assertive Knowledge (ABox, the concrete simulation model)
- Predefined, individual extendable standard ontology for
  - Transport logistics
  - Production logistics
  - Communication technology
  - Software / Web Services (DOLCE Core Software Ontology)
- Perception through sensor technology
**PlaSMA**

**Monitoring and Evaluation with PlaSMA**

- Geographic visualization is available
  - Scenario visualization using NASA World Wind
  - Applications for transport and intra-logistics, e.g. Bangalore:
    - Buses,
    - Persons,
    - Rickshaws

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**Autonomous Onward Container Carriage**

- Container haulage from port of discharge to warehouse
  1. Select appropriate warehouse
  2. Select means of transport
- Autonomous control with agent representatives (grouping in teams)
- Coordination of agents to achieve desired overall performance

Adapted from [Schuldt 2011]
Intelligent Container Scenario in \textit{PlaSMA}

Social Order Generation in Negotiations

\textbf{Sociological Foundations}
- Social order reduces contingency of interaction outcomes through expectations
- Social actors expect outcomes of activities
- Activity selection based on expectations
- Emergence of expectations from observations

\textit{[Luhmann, 1995; Dittrich et al., 2003]}

\textbf{Feedback Loop}
Concurrent Iterated Negotiations

Coordination challenges
1. Concurrent actions of several Initiators: Interrelated agent activities
2. Limited resources of participants: Competition between agents
3. Distributed decision-making: Partially observable environment

Agents must adapt their actions to each other
- Observe offers over several iterations
- Learn which provider to ask best
- Apply learned best response behavior (mutual best response = Nash equilibrium)

Distributed Learning in Iterated Negotiations

Distributed Q-learning for individual utility estimation
- Q-values $Q(a)$ for each action $a$
- Select best $\{a_1, \ldots, a_k\}$ according to $\varepsilon$-greedy
- Learn from reward $\sum_{i=1}^{k} Q(a_i)$
Distributed Learning in Iterated Negotiations

Distributed Q-learning for individual utility estimation

- Q-values \( Q(a) \) for each action \( a \)
- Select best \( \{a_1, \ldots, a_k\} \) according to \( \sum_i Q(a_i) \); \((\epsilon\text{-greedy})\)
- Learn from reward \( R(a_i) = U(\text{result}(a_i)) \)

Update rule (with learning rate \( \lambda \)):

\[
Q(a) \leftarrow Q(a) + \lambda \cdot (R(a) - Q(a))
\]

Convergence requirements (for \( t \to \infty \)):

- Non-zero selection probability for all actions
- Asymptotically exploitive selection (decaying sequence \( \epsilon_n \) with \( \lim_{t \to \infty} \epsilon_t = 0 \))

[Claus & Boutilier 1998]

Question: When to terminate the negotiation?

Approximating Utility Equilibria

Negotiation tactics to approximate utility equilibria

Minimally acceptable utility (reservation level) \( U_{\text{res}} \)

Monotonically decreasing acceptance level \( U_{\text{acc}} \)

- Valuate latest offer
- Terminate if utility exceeds acceptance level
- Otherwise: continue until \( U_{\text{acc}} < U_{\text{res}} \)

Time dependent tactics (deadline \( t_{\text{max}} \)):

\[
U_{\text{acc},t} = U_{\text{acc},0} - \left( U_{\text{acc},0} - U_{\text{res}} \right) \left( \frac{t}{t_{\text{max}}} \right)^\beta
\]

Adapted from [Faratin et al. 1998]
Empirical Evaluation (I)

Multiagent-based simulation (PlaSMA)

Experimental setup:
- \( n = 10 - 1000 \) agents, 500 simulation runs
- Action collision: 1 propose, others refuse
- Utility assessment:
  \[ U(result(a_i)) = \frac{1}{k} \begin{cases} 1 & \text{if } result(a_i) \text{ is propose message} \\ 0 & \text{otherwise} \end{cases} \]
- Parameters: \( \lambda = 0.4, \quad \epsilon_i = \frac{1}{(i+1)^2}, \quad U_{\text{res}} = 0.25, \quad U_{\text{acc},0} = 1, \quad t_{\text{max}} = 800 \)

Experiments and measured properties:
- Convergence to optimal resource allocation
- Approximation of optima depending on team sizes
- Required interaction effort

Empirical Evaluation (II)

Individual agent interaction

Results:
- Convergence to optimal performance
- Scales very well for large multiagent systems
Empirical Evaluation (III)

Capability to approximate optimal allocations depending on team size

- Approximation of optima even for large teams ($k = 40$)
- Boulware tactics lead to highest outcome utilities

Empirical Evaluation (IV)

Required interaction effort

- Conceder tactics impose lowest interaction effort
- Social order generation lowers interaction effort by itself
A Case Study in Container Logistics

Tchibo [Schuldt, 2010]
- 56,000 outlets in Europe
- Weekly changing range of consumer non-food products
- Significant differences in value, weight, volume
- 200-300 containers from China per week

Onward carriage process
- Centralised manual control
- Supported only by information systems
- Highly specialised task, low personnel redundancy

Participating Logistics Entities

Shipping containers
- Estimated time of arrival?
- Which port of discharge?
- When is the cargo to be sold?
- Similar articles received?
- Location of recent parts?
- Properties of the cargo?
- Detention?

Warehouses
- Which articles can be received?
- Which capacity?
- Time for receiving?
- Costs for storage and handling?

Ports of discharge
- Time for unloading?
- Demurrage?

Transport relations
- Which ones available?
- Which capacity?
- Cost and time for transport?
Simulation Experiment

11,521 shipping containers
in one year

cost(A) < cost(C) < cost(B)  cost(Barge) < cost(Train) < cost(Truck)

Utilisation of Storage Resources

Conservative strategy prevents storage fragmentation best
- Decision for storage provider is made late
- Chooses only facilities with capacity for all articles

Utilisation of the primary warehouse decreases
- Less possibility to fill remaining gaps with few articles
- Deferring decision-making prevents reserved resources from being re-allocated early
Utilisation of Transport Resources

Conservative strategy prevents excess capacity best
- Decision for transport provider is made late
- Considers minimum utilisation for means of mass transport

Utilisation of means of mass transport decreases
- More alternative warehouses used (connected only by truck)
- Shipping containers must switch to trucks if the minimum utilisation is not met

Comparison to Present Process Control

Real-world data from eight sales phases in 2006
- Choice of storage and transport providers comparable to human dispatcher

Better utilisation of cost free times at container terminals
- 45.5% utilisation by human dispatcher
- 68.3% utilisation by autonomous logistics entities
- Autonomous logistics would have saved space cost for 2.6 million pallet days per year

Exception handling
- Exceptions within system boundaries can be resolved
- Human dispatcher can be informed about other exceptions
- Dispatcher can solve exceptional cases more efficiently because he/she is relieved from standard tasks
References


A. Schuldt: Multiagent Coordination Enabling Autonomous Logistics. Springer-Verlag, Heidelberg, Germany, 2011.
Thank you very much for listening!

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