

60 Years of SAT Solving

– Applications to Automotive Configuration –

21 February 2020

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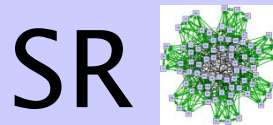
Dipl.-Inform., Dr. sc. techn. (ETH)

**Symbolic Computation Group
Wilhelm-Schickard-Institute of Informatics
Faculty of Mathematics and Sciences**

Universität Tübingen

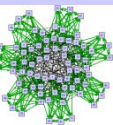
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Variant-rich automotive configuration

- Variant-rich „individualized mass production“
 - Configure 1 out of $\sim 10^{30}$ cars, observing Boolean constraints
- 2 Levels: Product description (PD) + parts list (BoM)
 - **High Level PD:** Which configurations can be built?
 - Boolean constraints system, $\sim 500\text{KB}$, 1000s constraints, $\sim 10^{30}$ solutions
 - Daimler: PÜ; VW: MBT; BMW: VRM; GM: VDS; Renault, Peugeot, ...
 - **Low Level BoM:** Which parts go into each configuration?
 - List of all (10,000s) parts for each model line (e.g. C Class, A4, Golf)
 - Boolean conditions (*if cond then part*) select the parts for each order
- **Mechanical Theorem Proving** → **Formal Verification**
 - verify properties, detect defects, answer queries, optimize
 - with respect to the full theoretical variance ($\sim 10^{30}$ orders)



Mercedes High-Level Product Description

Example: E-Class

- approx. 1.500 codes (options, countries, ..)
- approx. 3.000 rules in product overview (PÜ / PD)
- rule-based BOM with approx. 35,000 parts.
- B(code): condition for presence of code in order
- Z(code): condition for automatic addition of code



$B(P09) = 297+540+543;$

$B(610) = (512 / 527 / 528)+608+ -978;$

$Z(P09) = (M271 + -M013 / M272) + 830 /$
 $Z04+ -(M273 + Z27)$

$Z(682) = 623 / 830 / 513L$

$B(450) = L+965+ 670+837+ -P34+$
 $((M271/M651)+(953/955)+(100A/200A)+(334/335)+(301/336/337) /$
 $/ M642+(2XXL/557L/571L)+(953/955)+(100A/200A)+(334/335)+ (301/337));$



Low-Level Product Description (BOM)

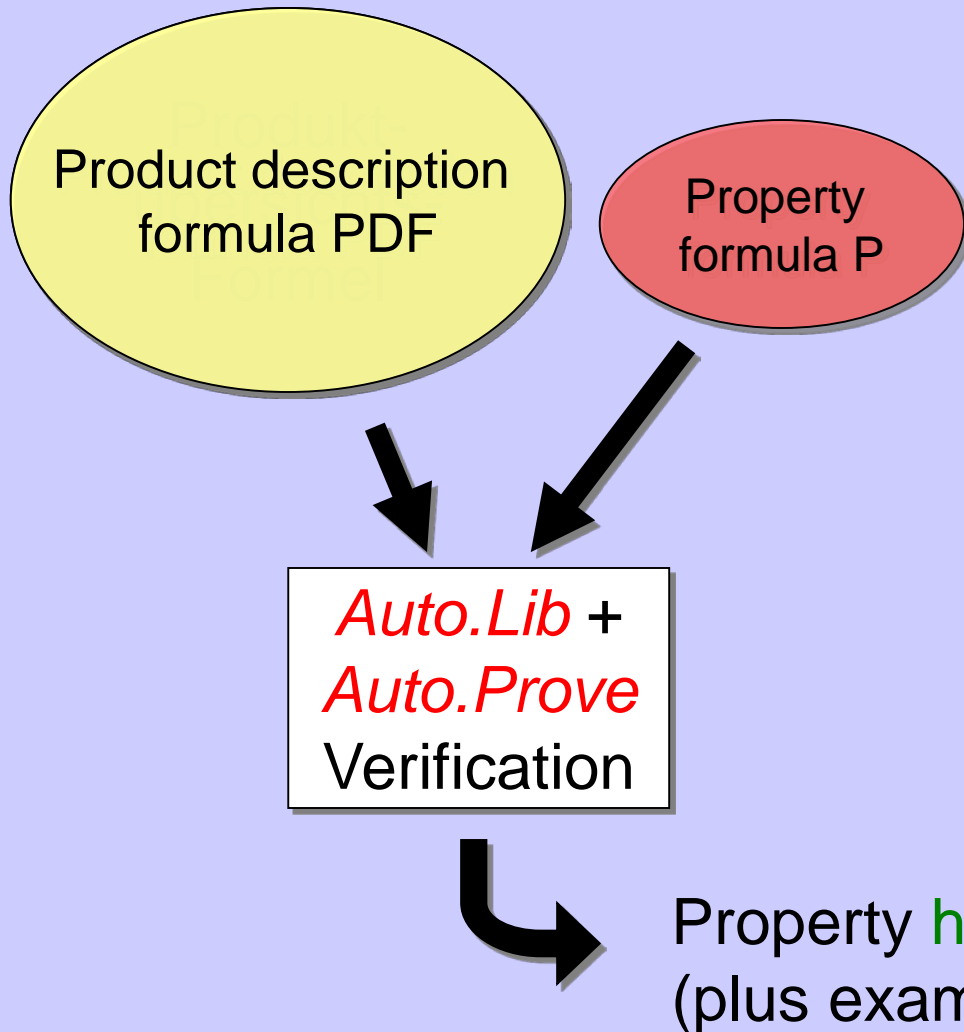
➤ BOM – Bill-of-Materials

- List of Materials (parts, software, colors) for entire car model line
- Grouped by Functionality (e.g. steering wheels, headlights,...)
- Within group: List of alternative parts (materials)
- List of Tupels: <Material, Boolean Selection Condition>

ZB	Benennung	Codebedingung
POS	ZB RAD 34R	
ZB	ZBU RAD MIT REIFEN 34R	
ZB	RAD / 7J X 16H2 + 205/55 R16 91V	34R+R01+V22;
ZB	RAD / 7J X 16H2 + 205/55 R16 91V	34R+R01+V22+(470/475);
ZB	RAD / 7J X 16H2 + 205/55 R16 91W	34R+R01+V50;
ZB	RAD / 7J X 16H2 + 205/55 R16 91W	34R+R01+V50+(470/475);
ZB	RAD / 7J X 16H2 + 205/55 R16 91H	34R+R01+V21;
ZB	RAD / 7J X 16H2 + 205/55 R16 91H	34R+R01+V21+(470/475);
ZB	RAD / 7J X 16H2 + 205/55 R16 91W	34R+R01+V50+M272+M35+M012;
ZB	RAD / 7J X 16H2 + 205/55 R16 91H AL...	34R+R02+V21;
ZB	RAD / 7J X 16H2 + 205/55 R16 91H M...	34R+645+V21;
ZB	RAD / 7J X 16H2 + 205/55 R16 91H M...	34R+645+V21+(470/475);
ZB	RAD / 7J X 16H2 + 205/55 R16 91H M...	34R+645+V21+M272+M35+M012;



Verification by *Auto.Prove* Mechanical Prover



Standard Checks on PD

- Codes which CANNOT be selected
- Codes which MUST be selected
- Per Model line, model, country ...

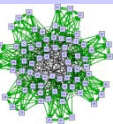
Standard Checks on BOM

- No-Hits (part is missing for some car)
- Double-Hits (some car gets 2 parts)
- Orphaned parts (no car gets the part)

Individual (free) Queries

- Codes optional in US,
- Parts deliverable to Japan, ...
- → **Configurator**

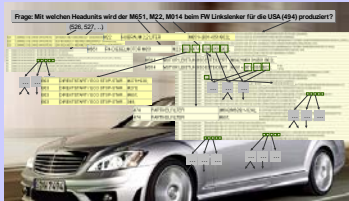
Property **holds always** / **does not hold always**
(plus example of car / proof for no car)



Query Example: Explaining PD Inconsistency

Ex: Country code 817L „Taiwan“ impossible for station wagon, model type Cxxx

Analysis of product description which yields contradiction and pinpoints the problem:



Auto.Prove

Code rule for 817L (Taiwan):	L+M272+M30
Code rule for M30 (displacement):	M642 / R
Code rule for M642 (engine):	-M272

Conclusion:

Taiwan (817L) requires L+M272+M30. Since engine displacement M30 with motor M272 requires right-hand steering R, no orders for Taiwan (817L) can be manufactured.

→ The product overview is defective / incomplete and the wagon is impossible for Taiwan!

Defects in the product overview can potentially cause significant damage (Mio Euros):

- Delivery of non certified Wheel/Tyre combinations to Asia
- Delivery of non certified aggregate combinations to China
- Delivery of headunits to Asia which can only display Latin characters



Our SAT based configurator framework **Auto.Config**

➤ Car configuration task

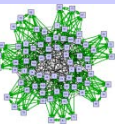
- User enters some option combination A+B+...
- User selects any option family F in any order (e.g. motors, seats, wheels ..)
- **Auto.Config** computes paths to success (SAT Solving the config rules)
 - which options in F can still be selected (which are implied / which are impossible)
 - and which BoM parts are already implied / which are impossible / still possible
- User selects an option O in F and repeats the process with A+B+O

➤ Re-configuration task

- User selects an impossible option O
- **Auto.Config** computes (using a MaxSAT algorithm)
 - **minimal change** to order (undo previous selections) so O can be selected

➤ Weak learning AI?

- we program only the **Config** framework, then load (learn?) PD and BoM **rules**
- If **Config** is wrong, **error** can be in **programming**, or in the **rules**



Example: Configuration with *Auto.Config*

- Start with a model
- *Auto.Config* computes arbitrary PD-valid order
- Select any option family
- **Bold:** *Auto.Config* computes options available for this model
- Grey: *Auto.Config* computes options not available for this model

The screenshot shows the AutoConfig software interface. The window title is "AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20". The interface includes a menu bar (File, Selection, Operations, Automatic Operations, Settings, About), an "Input Order" section with "#Options: 0" and "(Sum Priorities: 0)", and an "Output Order" section with "#Options: 188" and "(Sum Priorities: 0)". A "Next" button is located below the "Output Order" section. A grid of alphanumeric codes is displayed, with a green arrow pointing to the code "E3T". Below the grid, there are tabs for "Rules", "Custom Rules", and "Families". The "Families" tab is active, showing a table with columns "Selection", "Priority", "Name", and "Description". The table contains the following data:

Selection	Priority	Name	Description
<input type="checkbox"/>	0	E0A	Keine Aktionsausführung
<input type="checkbox"/>	0	E2A	Multivan Edition25
<input type="checkbox"/>	0	E3T	"Life"
<input type="checkbox"/>	0	E5T	Transporter Edition
<input type="checkbox"/>	0	E5U	California Edition
<input type="checkbox"/>	0	E79	"Special"

On the left side of the "Families" tab, there is a list of options. A green arrow points to the option "E3T" in the table, and a red arrow points to the option "E3T" in the list. The options in the list are: AAU (Aktionsausführungen), ABR (Abschließbare Radschrauben), AED (Fahrzeugklassendifferenzierung), AGM (Abgaskonzept), AHV (Anhängervorrichtung), AIB (Airbag), ALF (Ablagen Fahrerhaus), ALG (Ablagenpaket), ALV (Armlehnen für Vordersitze), ASE (Außenspiegel-Einstellung), ASG (Anschlussgarantie), ASL (Außenspiegel links), ASR (Außenspiegel rechts), AUD ("Multimedia"Video/-DVD/No), AUE (Achs- / Gangübersetzung), AUS (Ausstattungsstufen), BAT (Batterien), BBO (Bauteile mit besonderer Ober), BED (Bedienelemente (Lenkräder/Le), BEL (Instrumentenbeleuchtung), BFH (Bodenbeläge im Fahrerhaus), BFL (Bodenbeläge im Fahrgast- / La), BGK (Batterien/Generatoren Kapazi), BLB (Bauteilesatz länderspezifischer



Example: Configuration with *Auto.Config*

- Select any option family
- Select any available option
- *Auto.Config* re-computes PD-valid order with selected option
- **Bold:** *Auto.Config* computes options available for this input order
- Grey: *Auto.Config* computes options not available for this input order

AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20

File Selection Operations Automatic Operations Settings About

Input Order: E3T(1)
(#Options: 1)
(Sum Priorities: 1)

Output Order: 0E1 0FM 0G4 0GZ 0JZ 0KA 0TA 0WS 0Y2 0YZ 0ZN 1AN 1CP 1D7 1EY 1G8 1HA 1L0 1N3 1NL 1PA 1S0 1T1 1U3 1W0 1Y0 1Z0
(#Options: 188)
(Sum Priorities: 1)

Next

Rules Custom Rules Families

Selection	Priority	Name	Description
<input type="checkbox"/>	0	E0A	Keine Aktionsausführung
<input type="checkbox"/>	0	E2A	Multivan Edition25
<input checked="" type="checkbox"/>	1	E3T	"Life"
<input type="checkbox"/>	0	E5T	Transporter Edition
<input type="checkbox"/>	0	E5U	California Edition
<input type="checkbox"/>	0	E79	"Special"



Example: Configuration with *Auto.Config*

- Select any option family
- Select any available option
- *Auto.Config* re-computes PD-valid order with selected option
- **Bold:** *Auto.Config* computes options available for this input order
- Grey: *Auto.Config* computes options not available for this input order

The screenshot shows the AutoConfig software interface. The 'Input Order' is set to 'E3T(1) 1PC(1)'. The 'Output Order' is a long list of alphanumeric codes. A table below shows the 'Families' section with columns for Selection, Priority, Name, and Description. The table lists various options, with '1PC Radschrauben mit Diebstahlsicherung (nicht abschließbar)' selected and highlighted in bold.

Selection	Priority	Name	Description
<input type="checkbox"/>	0	1PA	Radschrauben Standard
<input checked="" type="checkbox"/>	1	1PC	Radschrauben mit Diebstahlsicherung (nicht abschließbar)

Example: Configuration with *Auto.Config*

- Select any option family
- Select any available option
- *Auto.Config* re-computes PD-valid order with selected option
- **Bold:** *Auto.Config* computes options available for this input order
- Grey: *Auto.Config* computes options not available for this input order

The screenshot shows the 'AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20' window. The 'Input Order' is set to 'E3T(1) 1PC(1) 7MG(1)'. The 'Output Order' is a long list of codes, with '7MG' and 'E3T' circled in green. A table below shows the 'Families' section with columns for Selection, Priority, Name, and Description. The '7MG' option is selected and bolded.

Selection	Priority	Name	Description
<input type="checkbox"/>	0	0GG	Abgaskonzept, EU4
<input type="checkbox"/>	0	0GV	Abgaskonzept, EU2 ddk (Dampfdruckkritisch)
<input type="checkbox"/>	0	0GZ	Abgaskonzept, EU3 Diesel m.EOBD
<input checked="" type="checkbox"/>	1	7MG	Abgaskonzept, EU5
<input type="checkbox"/>	0	7MH	Abgaskonzept, EU4 CN m.EOBD o. HWÄ
<input type="checkbox"/>	0	7MJ	Abgaskonzept, EU5 plus
<input type="checkbox"/>	0	7MQ	Abgaskonzept, EU5 mod
<input type="checkbox"/>	0	7MS	Abgaskonzept, EU5 CN



Example: Configuration with *Auto.Config*

- Select any option family
- Select any available option
- *Auto.Config* re-computes PD-valid order with selected option
- **Bold:** *Auto.Config* computes options available for this input order
- Grey: *Auto.Config* computes options not available for this input order

The screenshot shows the 'AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20' window. The 'Input Order' is 'E3T(1) 1PC(1) 7MG(1) 1D2(1)'. The 'Output Order' is a long list of codes, with '7MG' and 'E3T' circled in green. A table below shows the selection results for the 'Families' tab.

Selection	Priority	Name	Description
<input type="checkbox"/>	0	1D0	Ohne Anhängervorrichtung
<input type="checkbox"/>	0	1D1	Anhängervorrichtung
<input checked="" type="checkbox"/>	1	1D2	Anhängervorrichtung, abnehmbar und abschließbar
<input type="checkbox"/>	0	1D7	Vorbereitung für Anhängervorrichtung



Example: Configuration with **Auto.Config**

- Select any option family
- Grey: options not available for this input order
- **Bold**: available options in family for this input order

AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20

File Selection Operations Automatic Operations Settings About

Input Order: E3T(1) 1PC(1) 7MG(1) 1D2(1)
 (#Options: 4)
 (Sum Priorities: 4)

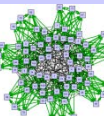
Output Order: 0E1 0FM 0G4 0JZ 0KA 0TA 0WN 0Y1 0YZ 0ZN 1AN 1C 1D2 1EX 1G8 1HZ 1L0 1N3 1N 1PC 1S0 1T1 1U3 1W0 1Y0 1Z0 2A0
 2E3 2G1 2JG 2KU 2MD 2N4 2P2 2PG 2Q0 2QE 2V5 2WA 2BT 2CX 2HA 2J3 2JA 2L3 2LQ 2M 2R0 2RC 2S4 2SF 2TF 2U5 2VX
 3W3 3WA 3Y7 3YR 4A3 4B2 4C2 4E8 4FN 4GF 4H6 4HH 4I2 4JH 4L2 4LA 4N3 4R1 4S1 4SM 4T 4UF 4X7 4Y0 5AD 5BG 5C0
 5C1 5D1 5DD 5FA 5G1 5K0 5MD 5N6 5NC 5Q2 5R2 5RT 5S6 5V3 6B3 6CE 6FB 6K0 6N3 6U1 6X1 6XN 7AA 7B0 7K0 7L3
 7MG P1 7Q0 7QA 7V0 7X2 7Y0 7YE 8AE 8EL 8FA 8GU 8K1 8N1 8Q1 8QJ 8RM 8SD 8T0 8TC 8WB 8X3 8Y0 8Z5 9CH 9H0 9JA
 9KA 9LA 9M0 9N3 9NA 9P0 9Q1 9WC 9Z0 9ZA A8E AEO AF0 AW5 B01 B0X C2G C3 E3T E39 EU0 F0A FC1 FM1 G0C GP0 GX3

Next

Rules Custom Rules Families

Selection	Priority	Name	Description
<input type="checkbox"/>	0	4UC	Airbag für Fahrer
<input type="checkbox"/>	0	4UE	Airbag für Fahrer und Beifahrer
<input type="checkbox"/>	0	4UF	Airbag für Fahrer und Beifahrer mit Beifahrer-Airbag-Deaktivierung

AAU (Aktionausführungen)
ABR (Abschließbare Radschrauben)
AED (Fahrzeugklassendifferenzierung)
AGM (Abgaskonzept)
AHV (Anhängervorrichtung)
AIB (Airbag)
ALF (Ablagen Fahrerhaus)
ALG (Ablagenpaket)
ALV (Armlehnen für Vordersitze)
ASE (Außenspiegel-Einstellung)
ASG (Anschlussgarantie)
ASL (Außenspiegel links)
ASR (Außenspiegel rechts)
AUD ("Multimedia"Video/-DVD/No...
AUE (Achsen- / Gangübersetzung)
AUS (Ausstattungsstufen)
BAT (Batterien)
BBO (Bauteile mit besonderer Ober...
BED (Bedienelemente (Lenkräder/Le...
BEL (Instrumentenbeleuchtung)
BFH (Bodenbeläge im Fahrerhaus)
BFL (Bodenbeläge im Fahrgast- / La...
BGK (Batterien/Generatoren Kapazi...
BLB (Bauteilesatz länderspezifischer...



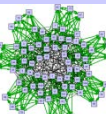
Optimization Ex.: **Re-Configuration with Auto.Config**

- Select an option **not** available
- **Auto.Config** computes **maximum** subset of PD-legal option selections
- **Auto.Config** computes **minimum** subset of **impossible** option selections
- **Auto.Config** computes new order containing the PD-legal options with **maximum sum of input weights** (here allways 1)

The screenshot shows the AutoConfig software interface. The 'Input Order' section lists options: E3T(1), 1PC(1), 7MG(1), 1D2(1), and 4UE(1). The 'Output Order' section lists a large set of options including 0E1, 0FM, 0G4, 0JJ, 0KA, 0TC, 0VD, 0WS, 0Y3, 0YM, 0ZN, 1AN, 1B3, 1CP, 1D2, 1EX, 1G3, 1HZ, 1L2, 1N3, 1N4, 1PC, 1S2, 1T3, 1U3, 1W0, 1Y0, 1Z3, 2A0, 2E3, 2G1, 2JG, 2KT, 2N4, 2P2, 2PW, 2Q0, 2QE, 2V5, 2WA, 2BA, 2CA, 2HB, 2J3, 2JB, 2L1, 2LQ, 2M7, 2R0, 2RC, 2S4, 2SQ, 2TF, 2U0, 2VE, 2W3, 2WA, 2Y7, 2YR, 2A3, 2B2, 2C0, 2E8, 2FH, 2GF, 2H6, 2HH, 2JH, 2K3, 2L2, 2LA, 2N3, 2R1, 2S1, 2SM, 2T1, 2UF, 2X3, 2Y0, 2AD, 2BG, 2K0, 2L1, 2L3, 2D1, 2DD, 2FA, 2G1, 2K0, 2MD, 2N6, 2N3, 2Q2, 2R2, 2RT, 2SL, 2V3, 2B3, 2CE, 2FB, 2KA, 2L0, 2N2, 2U1, 2X4, 2XN, 2AA, 2B3, 2K0, 2L1, 2L3, 2P7, 2Q0, 2QA, 2V0, 2X0, 2Y0, 2BAE, 2EL, 2FA, 2GU, 2K1, 2N1, 2Q1, 2QJ, 2RE, 2SA, 2TB, 2TC, 2WH, 2X4, 2Y1, 2Z5, 2CH, 2H0, 2JC, 2KA, 2LA, 2M0, 2N3, 2NA, 2P1, 2Q1, 2W0, 2XC, 2Z0, 2AE, 2E0, 2F0, 2W5, 2B0, 2B0, 2C3, 2D0, 2E3, 2J9, 2U0, 2F0A, 2FC1, 2FM1, 2G0C, 2GP0, 2GX3.

The 'Rules' section shows a list of rules, with '4UC' selected. The 'Families' section shows a table of configurations:

Selection	Priority	Name	Description
<input type="checkbox"/>	0	4UC	Airbag für Fahrer
<input checked="" type="checkbox"/>	1	4UE	Airbag für Fahrer und Beifahrer
<input type="checkbox"/>	0	4UF	Airbag für Fahrer und Beifahrer mit Beifahrer-Airbag-Deaktivierung



Optimization Ex.: **Re-Configuration with Auto.Config**

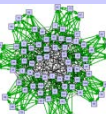
- **Re-Configuration**
- Fix the unavailable option 4UE(*)
- **Auto.Config** computes **maximum** subset of PD-legal option selections
- **Auto.Config** computes **minimum** subset of impossible option selections

The screenshot shows the AutoConfig software interface. The title bar reads "AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20". The menu bar includes "File", "Selection", "Operations", "Automatic Operations", "Settings", and "About".

The "Input Order" section shows a list of options: E3T(1), 1PC(1), 7MG(1), 1D2(1), and 4UE*. The "Output Order" section shows a list of 188 options, including 1D0, 1PC, 4UE, and E3T. A table below shows the selection status for three options:

Selection	Priority	Name	Description
<input type="checkbox"/>	0	4UC	Airbag für Fahrer
<input checked="" type="checkbox"/>	*	4UE	Airbag für Fahrer und Beifahrer
<input type="checkbox"/>	0	4UF	Airbag für Fahrer und Beifahrer mit Beifahrer-Airbag-Deaktivierung

Green circles highlight the input options E3T(1), 1PC(1), 7MG(1), 1D2(1), and 4UE*. A red arrow points from the text "Fix the unavailable option 4UE(*)" to the 4UE* option in the input order. Another red arrow points from the text "Auto.Config computes maximum subset of PD-legal option selections" to the 4UE* option in the output order. A third red arrow points from the text "Auto.Config computes minimum subset of impossible option selections" to the 4UC option in the table.



Optimization Ex.: **Re-Configuration with Auto.Config**

- **Re-Configuration**
- Fix the unavailable option 4UE(*)
- **Auto.Config** computes **maximum** subset of PD-legal option selections
- **Auto.Config** computes **minimum** subset of impossible option selections
- **Auto.Config** computes new order **maximizing the weight** of the PD-legal input options

The screenshot shows the AutoConfig software interface. The title bar reads "AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20". The menu bar includes "File", "Selection", "Operations", "Automatic Operations", "Settings", and "About".

The "Input Order" field contains: E3T(1) 1PC(1) 7MG(1) 1D2(1) 4UE*
(#Options: 5)
(Sum Priorities: 4)

The "Output Order" field contains a list of 188 options, with 4UE and E3T circled in green. A green arrow points from the text "computes new order maximizing the weight of the PD-legal input options" to the "Next" button.

The "Rules" tab is active, showing a list of rules on the left and a table on the right.

Selection	Priority	Name	Description
<input type="checkbox"/>	0	4UC	Airbag für Fahrer
<input checked="" type="checkbox"/>	*	4UE	Airbag für Fahrer und Beifahrer
<input type="checkbox"/>	0	4UF	Airbag für Fahrer und Beifahrer mit Beifahrer-Airbag-Deaktivierung

Optimization Ex.: **Re-Configuration with Auto.Config**

- **Re-Configuration**
- Fix (*) the unavailable options 7MG, 4UE
- **Auto.Config** finds **contradiction**: no legal order with 7MG + 4UE

The screenshot shows the AutoConfig software interface. The title bar reads "AutoConfig - Prototyp (STZ OIT Tübingen) - Version 2014-11-20". The menu bar includes "File", "Selection", "Operations", "Automatic Operations", "Settings", and "About".

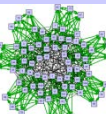
The "Input Order" field contains "E3T(1) 1PC(1) 7MG* 1D2(1) 4UE*", with the asterisk on 7MG and 4UE highlighted in red. Below it, it says "(#Options: 5) (Sum Priorities: 3)".

The "Output Order" field contains "No Order", with a red arrow pointing to it from the text on the left. Below it, it says "(#Options: 0) (Sum Priorities: 0)".

A "Next" button is located below the "Output Order" field.

The interface has three tabs: "Rules", "Custom Rules", and "Families". The "Rules" tab is active, showing a list of rules on the left and a table on the right.

Selection	Priority	Name	Description
<input type="checkbox"/>	0	4UC	Airbag für Fahrer
<input checked="" type="checkbox"/>	*	4UE	Airbag für Fahrer und Beifahrer
<input type="checkbox"/>	0	4UF	Airbag für Fahrer und Beifahrer mit Beifahrer-Airbag-Deaktivierung



Other Problems

➤ Compute all combinations of a set of materials

- given the materials in a subset of the BoM (e.g. driver's seat, rear axle, ...)
- From each BoM position pick exactly one material variant
- Compute all consistent combinations which can occur in configurable vehicles
- Example: All seats or all axles which can occur in a model line

➤ Compute software upgrades

- given software variants and their upgrade dependencies
- compute possible upgrades / compute all cars with possible upgrades

➤ Compute homologation (certification) requirements

- given a sales program for a market
- compute all homologation relevant materials for that market

➤ Change the documentation method

- convert the formulas for a car model line from one documentation method to another, preserving the set of legal configurations.
-



Literature

1. W. KÜchlin, C. Sinz. Proving Consistency Assertions for Automotive Product Data Management. *J. Automated Reasoning* **24** (2000)
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