Appendix A Results

In this section, we provide some additional information about the experiments, and present the results for every solver and configuration.

We note that in conditional planning, CPASP receives as input an additional width parameter that determines the minimum number of branches of a conditional plan. QASP2QBF receives no information of that kind, and in this regard it solves a more difficult task than CPASP. On the other hand, that width parameter allows CPASP to return the complete conditional plan, while QASP2QBF only returns the assignment to the first action of the plan. Observe also that given that CPASP is incomplete, in some instances QASP2QBF can find plans for OPT whose length is smaller than the fixed length of SAT. This explains why in some few cases QASP2QBF solves faster the OPT problem than SAT.

In the experiments, the times for grounding and for the translators LP2NORMAL and LP2SAT are negligible, while, in the SAT problem, preprocessing takes on average 5 and 2 seconds in conformant and conditional planning, respectively. We expect these times to be similar for the OPT problem. The reported times are dominated by CLINGO's solving time in CPASP, and by the QBF solvers in QASP2QBF. But the usage of preprocessors is fundamental for the performance of QASP2QBF. For example, in conformant planning, CAQE alone results in 18 timeouts, while with QRATPRE+ they go down to only 6.

	CLINGO^{C}		CLINGO^{F}		CLINGO^{H}		CLINGO^{J}		CLINGO^{R}		CLINGO^{T}	
Bt	52 (0)	0	176 (0)	0	362 (1)	0	43 (0)	0	363 (1)	0	48 (0)	0
Bmt	49 (0)	0	163 (0)	0	238 (0)	0	50 (0)	0	363 (1)	0	35 (0)	0
Btc	236 (0)	0	395 (1)	0	375 (1)	0	258 (0)	0	380 (1)	0	282 (0)	0
Bmtc	746 (2)	211	998 (2)	0	743 (2)	0	744 (2)	0	773 (2)	0	739 (2)	0
Btuc	367 (1)	0	389 (1)	0	372 (1)	0	245 (0)	0	382 (1)	0	380 (1)	0
Bmtuc	749 (2)	0	938 (2)	0	741 (2)	0	739 (2)	0	778 (2)	0	742 (2)	0
Domino	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0
Ring	774 (2)	506	1102 (3)	777	538 (1)	96	673 (1)	416	645 (1)	204	803 (2)	364
Ringu	1800 (5)	0	1800 (5)	0	1800 (5)	0	1800 (5)	0	1800 (5)	0	1800 (5)	0
Total	530 (12)	79	662 (14)	86	574 (13)	10	505 (10)	46	609 (14)	22	536 (12)	40

Table A 1. *Conformant planning with* CLINGO

	CAQE^{O}		CAQE^{B}		CAQE^{H}		CAQE^{Q}	
Bt	69 (0)	3	377 (0)	1	364 (1)	1	46 (0)	0
Bmt	44 (0)	3	149 (0)	4	373 (1)	11	155 (0)	2
Btc	440 (1)	3	487 (1)	3	577 (1)	13	413 (1)	1
Bmtc	814 (2)	7	777 (2)	7	1083 (3)	32	771 (2)	9
Btuc	476 (1)	3	475 (1)	3	606 (1)	9	400 (1)	1
Bmtuc	849 (2)	14	789 (2)	15	1260 (3)	25	780 (2)	14
Domino	1500 (5)	1500	0 (0)	0	0 (0)	0	0 (0)	0
Ring	1104 (3)	1097	219 (0)	30	837 (2)	793	281 (0)	40
Ringu	1630 (4)	1643	1018 (2)	969	1506 (4)	1505	246 (0)	45
Total	769 (18)	474	476 (8)	114	734 (16)	265	343 (6)	12

Table A 2. *Conformant planning with* CAQE

	DEPQBF$^{\circ}$		DEPQBF^{B}		DEPQBF^{H}		DEPQBF^{Q}	
Bt	740 (2)	0	744 (2)	1	363 (1)	1	319 (0)	0
Bmt	974 (2)	2	1089 (3)	3	372 (1)	11	367 (1)	2
Btc	1111 (3)	3	1084 (3)	3	729 (2)	10	566 (1)	2
Bmtc	1494 (4)	5	1442 (4)	7	1082 (3)	20	1083 (3)	9
Btuc	1102 (3)	7	1088 (3)	3	730 (2)	11	538 (1)	1
Bmtuc	1479 (4)	82	1443 (4)	8	1440 (4)	39	1085 (3)	12
Domino	0 (0)	0	1 (0)	0	0 (0)	0	0 (0)	0
Ring	1800 (5)	1800	1708 (4)	1468	1108 (3)	736	1120 (3)	1109
Ringu	1800 (5)	1800	1800 (5)	1800	1800 (5)	1800	1800 (5)	1800
Total	1166 (28)	411	1155 (28)	365	847 (21)	292	764 (17)	326

Table A 3. *Conformant planning with* DEPQBF

	QESTO$^{\circ}$		QESTO^{B}		QESTO^{H}		QESTO^{Q}	
Bt	725 (2)	3	458 (1)	1	363 (1)	1	57 (0)	0
Bmt	1081 (3)	9	443 (1)	4	372 (1)	13	76 (0)	1
Btc	1081 (3)	7	777 (2)	6	729 (2)	9	394 (1)	1
Bmtc	1440 (4)	20	1104 (3)	23	1082 (3)	23	826 (2)	9
Btuc	1082 (3)	15	736 (1)	6	734 (2)	9	391 (1)	2
Bmtuc	1441 (4)	359	1094 (3)	27	1286 (3)	26	813 (2)	12
Domino	1319 (4)	1339	0 (0)	0	0 (0)	0	0 (0)	0
Ring	1105 (3)	1096	499 (1)	30	782 (2)	752	790 (2)	392
Ringu	1800 (5)	1800	1444 (4)	1440	1800 (5)	1800	1800 (5)	1800
Total	1230 (31)	516	728 (16)	170	794 (19)	292	571 (13)	246

Table A 4. *Conformant planning with* QESTO

	QUTE$^{\circ}$		QUTE^{B}		QUTE^{H}		QUTE^{Q}	
Bt	864 (2)	3	1081 (3)	1	363 (1)	42	852 (2)	0
Bmt	1095 (3)	9	1180 (3)	3	382 (1)	12	477 (1)	1
Btc	1095 (3)	16	1093 (3)	3	729 (2)	38	1093 (3)	1
Bmtc	1453 (4)	27	1444 (4)	8	1082 (3)	374	1484 (4)	9
Btuc	1111 (3)	55	1101 (3)	3	731 (2)	38	1116 (3)	1
Bmtuc	1501 (4)	557	1745 (4)	24	1440 (4)	378	1483 (4)	12
Domino	1238 (4)	1239	0 (0)	0	0 (0)	0	0 (0)	0
Ring	1800 (5)	1449	1702 (4)	1441	1441 (4)	1440	1460 (4)	1208
Ringu	1800 (5)	1800	1800 (5)	1599	1800 (5)	1800	1800 (5)	1800
Total	1328 (33)	572	1238 (29)	342	885 (22)	458	1085 (26)	336

Table A 5. *Conformant planning with* QUTE

	CLINGO^{C}		CLINGO^{F}		CLINGO^{H}		CLINGO^{J}		CLINGO^{R}		CLINGO^{T}	
Bts1	1041 (2)	121	1080 (3)	77	795 (2)	49	989 (2)	51	916 (2)	28	927 (2)	370
Bts2	1080 (3)	60	1080 (3)	361	787 (2)	26	986 (2)	30	920 (2)	66	1080 (3)	71
Bts3	993 (2)	85	1071 (2)	215	802 (2)	82	1012 (2)	50	944 (2)	68	1080 (3)	253
Bts4	1060 (2)	69	1080 (3)	115	833 (2)	76	882 (2)	102	904 (2)	70	1080 (3)	173
Domino	872 (2)	15	885 (2)	59	906 (2)	6	771 (2)	13	786 (2)	7	759 (2)	18
Med	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0
Ring	902 (2)	900	905 (2)	900	902 (2)	900	903 (2)	900	902 (2)	900	902 (2)	900
Sick	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0	0 (0)	0
Total	743 (13)	156	762 (15)	215	628 (12)	142	692 (12)	143	671 (12)	142	728 (15)	223

Table A 6. *Conditional planning with* CLINGO

	CAQE$^{\circ}$		CAQE^{B}		CAQE^{H}		CAQE^{Q}	
Bts1	370 (1)	368	14 (0)	3	16 (0)	3	366 (1)	363
Bts2	378 (1)	376	14 (0)	3	15 (0)	4	106 (0)	54
Bts3	372 (1)	379	15 (0)	4	19 (0)	7	135 (0)	65
Bts4	374 (1)	384	17 (0)	4	25 (0)	8	107 (0)	53
Domino	372 (1)	365	362 (1)	125	366 (1)	297	223 (0)	113
Med	1095 (3)	1440	3 (0)	1	2 (0)	0	4 (0)	2
Ring	1350 (3)	1350	902 (2)	640	901 (2)	901	904 (2)	901
Sick	729 (2)	729	1 (0)	0	1 (0)	1	64 (0)	63
Total	630 (13)	673	166 (3)	97	168 (3)	152	238 (3)	201

Table A 7. *Conditional planning with* CAQE

	DEPQBF$^{\circ}$		DEPQBF^{B}		DEPQBF^{H}		DEPQBF^{Q}	
Bts1	722 (2)	720	364 (1)	361	396 (1)	366	721 (2)	506
Bts2	724 (2)	720	369 (1)	41	489 (1)	362	723 (2)	720
Bts3	729 (2)	720	372 (1)	10	721 (2)	361	726 (2)	720
Bts4	745 (2)	720	368 (1)	362	722 (2)	654	731 (2)	720
Domino	474 (1)	158	361 (1)	48	366 (1)	7	376 (1)	360
Med	2 (0)	0	3 (0)	1	2 (0)	0	1 (0)	0
Ring	1340 (2)	1350	901 (2)	900	902 (2)	901	902 (2)	902
Sick	55 (0)	48	1 (0)	0	1 (0)	0	0 (0)	0
Total	598 (11)	554	342 (7)	215	449 (9)	331	522 (11)	491

Table A 8. *Conditional planning with* DEPQBF

	QESTO$^{\circ}$		QESTO^{B}		QESTO^{H}		QESTO^{Q}	
Bts1	380 (1)	373	102 (0)	65	369 (1)	42	400 (1)	391
Bts2	384 (1)	379	370 (1)	182	720 (2)	720	390 (1)	378
Bts3	390 (1)	379	371 (1)	364	722 (2)	362	396 (1)	377
Bts4	392 (1)	382	379 (1)	89	721 (2)	720	392 (1)	379
Domino	720 (2)	413	363 (1)	5	366 (1)	360	530 (1)	481
Med	1100 (3)	1440	3 (0)	1	1 (0)	0	5 (0)	6
Ring	1350 (3)	1350	902 (2)	900	902 (2)	900	905 (2)	902
Sick	739 (2)	736	1 (0)	1	1 (0)	0	11 (0)	11
Total	681 (14)	681	311 (6)	200	475 (10)	388	378 (7)	365

Table A 9. *Conditional planning with* QESTO

	QUTE$^{\circ}$		QUTE^{B}		QUTE^{H}		QUTE^{Q}	
Bts1	770 (2)	760	365 (1)	361	724 (2)	722	751 (2)	726
Bts2	1080 (3)	1080	376 (1)	368	724 (2)	721	1080 (3)	1080
Bts3	896 (2)	901	380 (1)	370	783 (2)	777	1080 (3)	944
Bts4	966 (2)	916	390 (1)	377	731 (2)	726	1081 (3)	1080
Domino	722 (2)	408	361 (1)	360	720 (2)	720	606 (1)	451
Med	1104 (3)	1440	3 (0)	1	5 (0)	3	27 (0)	24
Ring	1350 (3)	1350	901 (2)	900	907 (2)	903	917 (2)	911
Sick	782 (2)	776	1 (0)	0	1 (0)	1	6 (0)	6
Total	958 (19)	953	347 (7)	342	574 (12)	571	693 (14)	652

Table A 10. *Conditional planning with* QUTE

Appendix B ASP(Q) and QASP

An ASP(Q) program Π is an expression of the form:

$$\Box_0 P_0 \Box_1 P_1 \cdots \Box_n P_n : C, \tag{B1}$$

where $n \geq 0$, $P_0, \ldots, P_n$ are logic programs, every $\Box_i$ is either $\exists^{st}$ or $\forall^{st}$, and C is a normal stratified program. In (Amendola et al. 2019), the logic programs P_i can be disjunctive. Here, for simplicity, we restrict ourselves to logic programs as defined in the Background section. Symbols $\exists^{st}$ and $\forall^{st}$ are called existential and universal answer set quantifiers, respectively. We say that the program P_i is existentially (universally, respectively) quantified if $\Box_i$ is $\exists^{st}$ ($\forall^{st}$, respectively). Let X and Y be sets of atoms such that $X \subseteq Y$, by $\mathit{fixfact}(X, Y)$ we denote the set of rules $\{x \leftarrow \mid x \in X\} \cup \{\leftarrow x \mid x \in Y \setminus X\}$. Let $\mathit{atoms}(P)$ denote the set of atoms occurring in a logic program P. Given an ASP(Q) program Π, a logic program P, and a set of atoms X, we denote by $\Pi_{P,X}$ the program of the form (B1), where P_0 is replaced by $P_0 \cup \mathit{fixfact}(X, \mathit{atoms}(P))$, that is, $\Pi_{P,X} = \Box_0(P_0 \cup \mathit{fixfact}(X, \mathit{atoms}(P))) \cdots \Box_n P_n : C$. The coherence of ASP(Q) programs can be defined recursively as follows:

- $\exists^{st} P : C$ is coherent, if there exists $M \in SM(P)$ such that $C \cup \mathit{fixfact}(M, \mathit{atoms}(P))$ is satisfiable;
- $\forall^{st} P : C$ is coherent, if for every $M \in SM(P)$, $C \cup \mathit{fixfact}(M, \mathit{atoms}(P))$ is satisfiable;
- $\exists^{st} P \Pi$ is coherent, if there exists $M \in SM(P)$ such that $\Pi_{P,M}$ is coherent.
- $\forall^{st} P \Pi$ is coherent, if for every $M \in SM(P)$, $\Pi_{P,M}$ is coherent.

Before moving to the translations between ASP(Q) and QASP, we introduce some special forms of ASP(Q) programs. We say that an ASP(Q) program of the form (B1) is in normal form if C is empty and the heads of the rules of every P_i do not contain atoms occurring in any P_j such that $j < i$, and we say that an ASP(Q) program is in $\forall$-GDT form if all its universally quantified logic programs are in GDT form. ASP(Q) programs of the form (B1) can be translated to ASP(Q) programs in normal and $\forall$-GDT form (using auxiliary variables) following the next steps:

1. Replace program C by $\emptyset$, and add $\exists^{st} C$ after $\Box_n P_n$.
2. In every logic program, replace the normal rules $p \leftarrow B$ such that p occurs in some previous program by constraints $\bot \leftarrow \neg p, B$; and erase the choice rules $\{p\} \leftarrow B$ such that p occurs in some previous program.
3. Apply the method described in (Niemelä 2008; Fandinno et al. 2020) to translate the universally quantified programs to GDT form.

The translation can be computed in polynomial time on the size of the ASP(Q) program, and the result is an ASP(Q) program in normal and $\forall$-GDT form that is coherent if and only if the original ASP(Q) program is coherent.

Once an ASP(Q) program Π of the form (B1) is in normal and $\forall$-GDT form, we can translate it to a QLP as follows. Let $qlp(\Pi)$ be the QLP of the form

$$Q_0 X_0 Q_1 X_1 \ldots Q_n X_n \big(P_0^\bullet \cup P_1^\bullet \cup \ldots \cup P_n^\bullet \cup O\big)$$

where for every $i \in \{0, \ldots, n\}$, if $\Box_i$ is $\exists^{st}$ then Q_i is $\exists$, X_i is the set of atoms occurring in P_i that do not occur in any previous program, and $P_i^\bullet$ is P_0 if $n = 0$ and otherwise it is the program that results from adding the literal $\neg\alpha_i$ to the body of every rule of P_i; while if $\Box_i$ is $\forall^{st}$ then Q_i is $\forall$, X_i is $\{p \mid \{p\} \leftarrow \in P_i\}$, and $P_i^\bullet$ is the program that results from replacing $\bot$ in the head of every integrity constraint by α_i; and O is $\{\alpha_i \leftarrow \alpha_{i-1} \mid \beta \leq i \leq n\}$ where β is 1 if $\Box_0 = \forall^{st}$ and is 2 otherwise.

Theorem Appendix B.1
Π is coherent if and only if $qlp(\Pi)$ is satisfiable.

The translation in the other direction is as follows. Given a QLP $\mathcal{Q}P$ over $\mathcal{A}$ of the form (2), let $aspq(\mathcal{Q}P)$ be the ASP(Q) program of the form

$$Q_0^{st} P_0 Q_1^{st} P_1 \ldots Q_n^{st} P_n \exists^{st} (P \cup O) : \emptyset$$

where every P_i is $\{\{p'\} \leftarrow \mid p \in X_i\}$, O is $\{\bot \leftarrow p, \neg p' \mid p \in \mathcal{X}\} \cup \{\bot \leftarrow \neg p, p' \mid p \in \mathcal{X}\}$ where $\mathcal{X} = \bigcup_{i \in \{0,\ldots,n\}} X_i$, and we assume that the set $\{p' \mid p \in \mathcal{X}\}$ is disjunct from $\mathcal{A}$.

Theorem Appendix B.2
$\mathcal{Q}P$ is satisfiable if and only if $aspq(\mathcal{Q}P)$ is coherent.